Field Applications of Non-Conventional Reinforcing and Strengthening Methods for Bridges and Structures, Part 1 of 3 (Speaker Schedule)

Moderator: Jimmy Kim *(Steve Nolan support) 5 x 20 min. presentations + 3 min. Q&A each.*

1:05 pm **Using a Prestressed Mechanically Fastened FRP Plate for Strengthening Bridges in N.C.**

Rudolf Seracino *(North Carolina State University)*

1:28 pm **Prestressing with GFRP Bars and Strands for Substructure Applications**

Marco Rossini *(University of Miami)*

1:51 pm **US-41 over North Creek; FRP-RC 2-Span Flat Slab Bridge and CFRP-PC/ GFRP-RC Substructure & Bulkhead**

Joe Losaria *(Patel, Greene and Associates)*

2:14 pm **CFRP-PC/GFRP-RC Harkers Island Bridge Replacement Project**

Trey Carroll (North Carolina DOT)

2:37 pm **US-1 over Cow Key Channel Span Replacements with CFRP/GFRP-PC Florida Slab-Beams -** Luis Vargas (Bolton Perez)

Using a Prestressed Mechanically Fastened FRP Plate for Strengthening Bridges in NC

Rudolf (Rudi) Seracino
Professor and Associate Head of Department

Sheng-Hsuan (Mike) Lin and Gregory Lucier
Department of Civil, Construction and Environmental Engineering
North Carolina State University

Field Applications of Non-Conventional Reinforcing and Strengthening Methods for Bridges and Structures

ACI Fall 2020 Virtual Convention

- ❑ Introduction
  - ❑ Background
  - ❑ Retrofit concept
  - ❑ Retrofit design
- ❑ Predicted Global Behavior
  - ❑ Layered-sectional analysis
  - ❑ Second-order effect
  - ❑ Predicted results
- ❑ Field Demonstration Project
  - ❑ Franklin County Bridge
  - ❑ Sampson County Bridge
- ❑ Conclusions

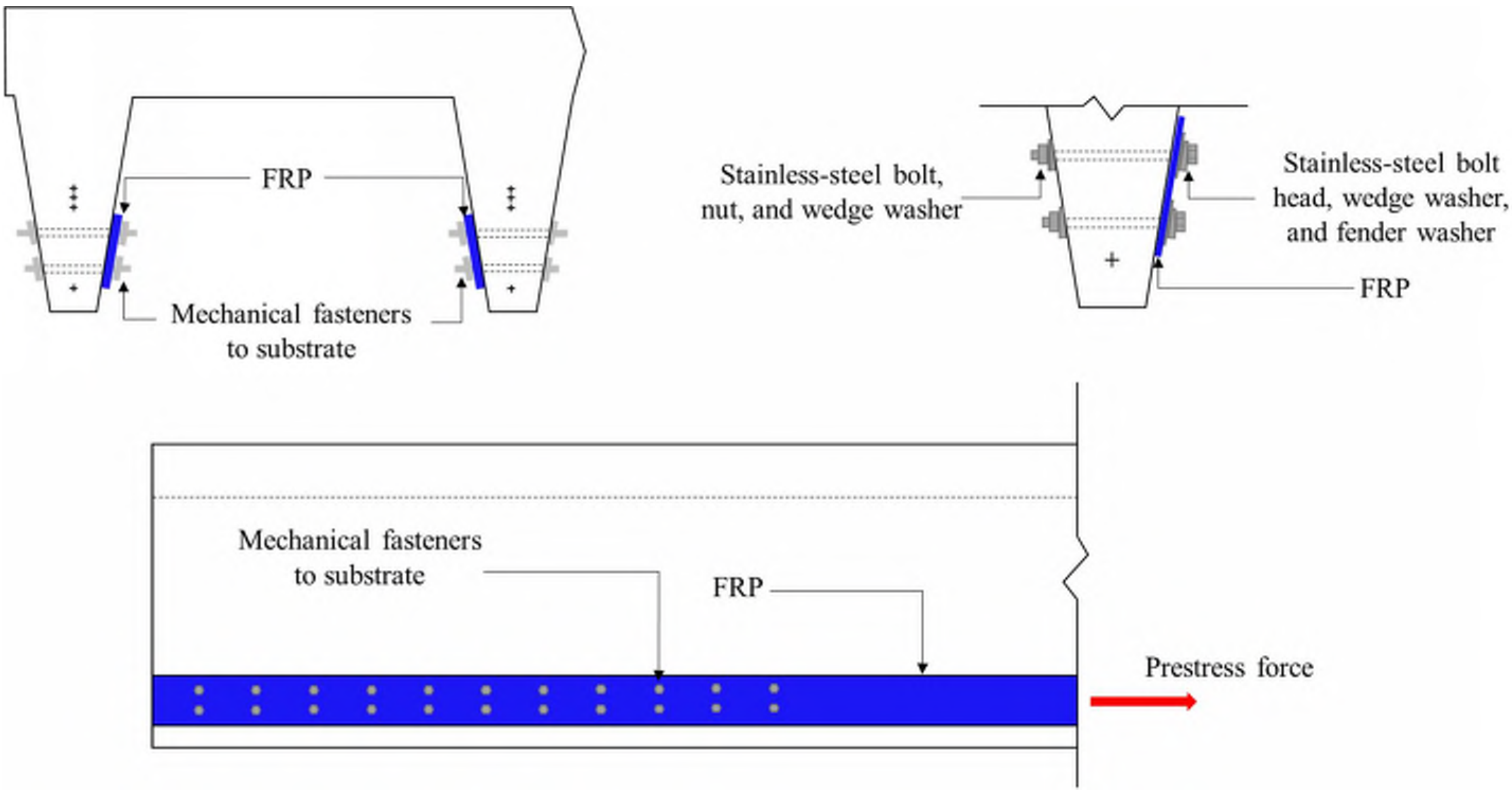
Background

- AASHTO Load Limit
  - Inventory rating
    - Routine traffic
    - No incremental damage
    - ***Zero tensile stress*** in concrete
  - Operating rating
    - Infrequent, heavier traffic
    - Small incremental damage
    - ***Maximum live load*** permissible

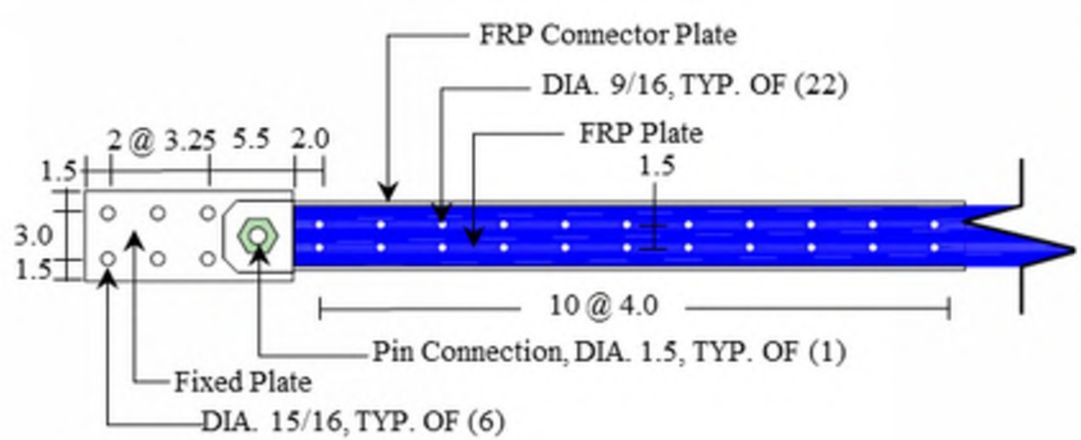
- State of C-Channel Beams in NC
  - Approximately 80% of 269 bridges are load posted
  - Average detour: 7.5 miles
  - Increased travel time
    - School bus: 22 minutes
    - Fire truck: 14 minutes

- MF-FRP Repair System
  - Rapid installation
  - Common tools & equipment
  - Restore prestress loss
  - Simple FRP prestress process

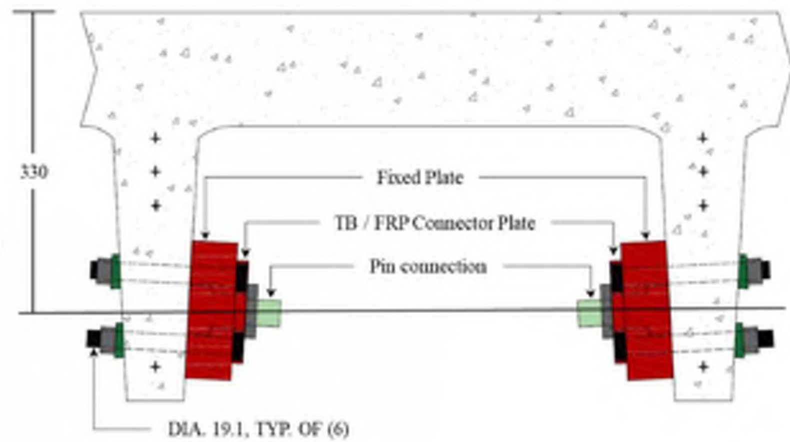
Original Retrofit Concept – C-Channel Beams



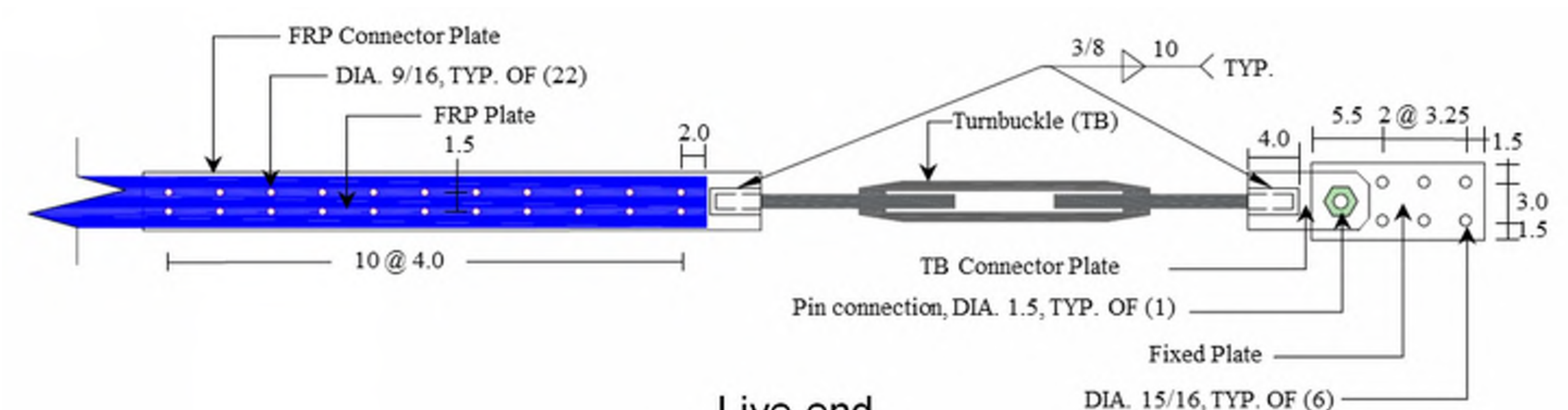
MF-FRP 2.0 Design Details



Dead-end

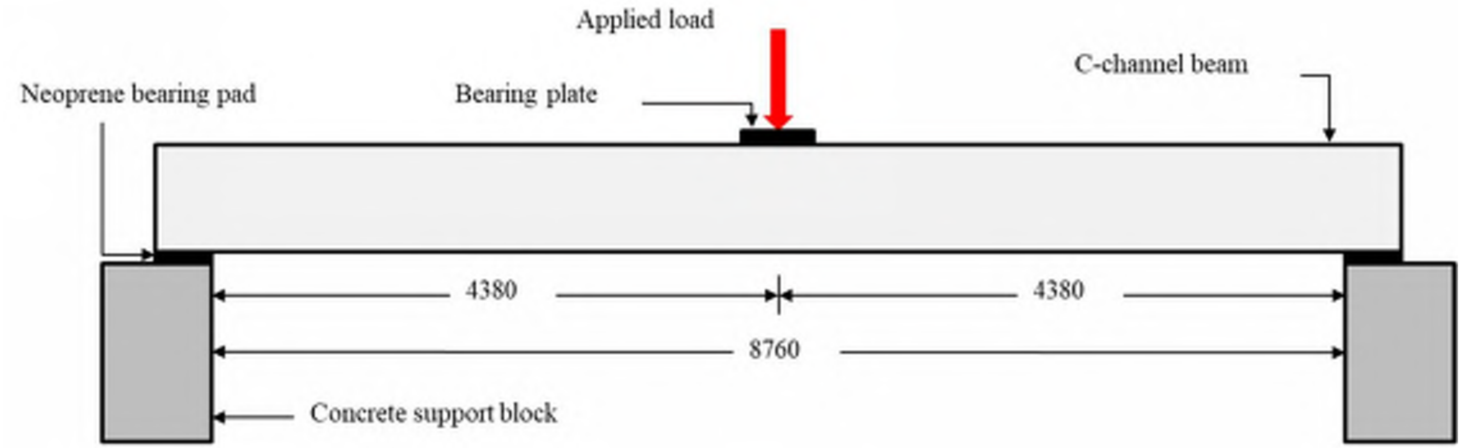


Cross-section detail



Live-end

Large-Scale Laboratory Experiments

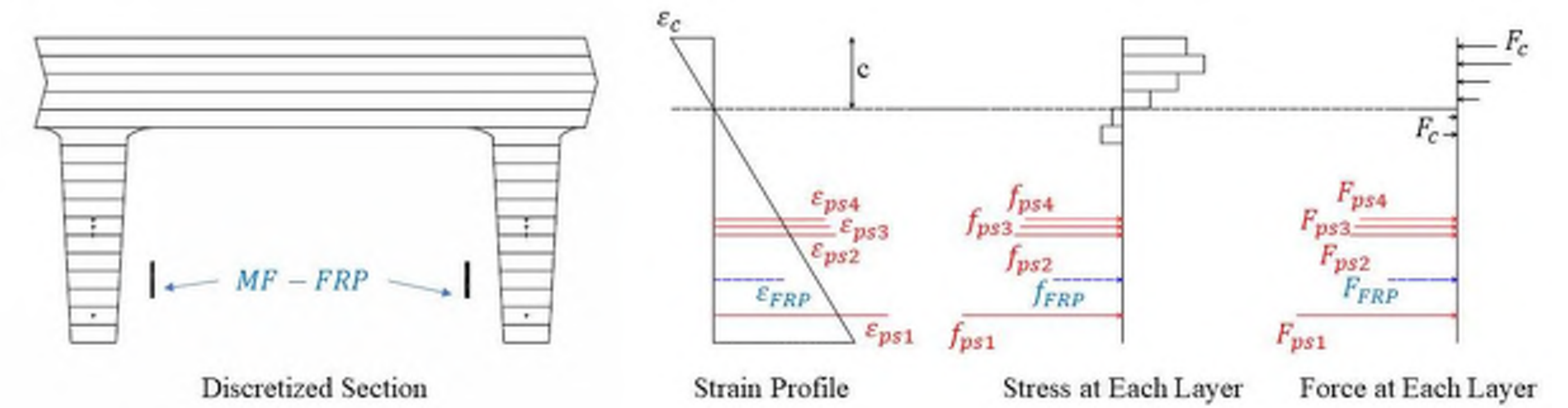


Dead-end

Live-end

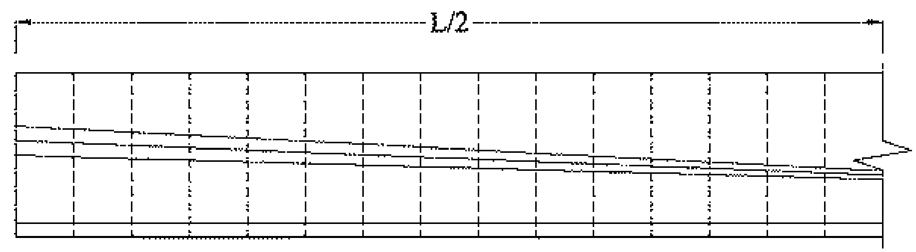
Predicted Global Behavior

- ❑ **Layered-Sectional Analysis – Moment and Curvature**



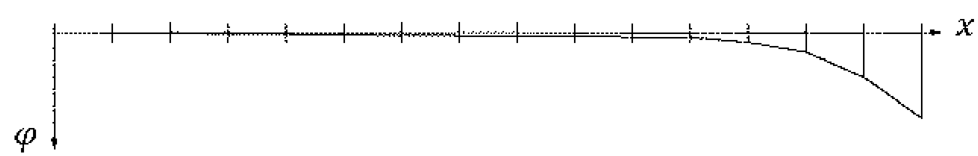
- ❑ **Moment-Area Method – Deflection**

Discretized Member



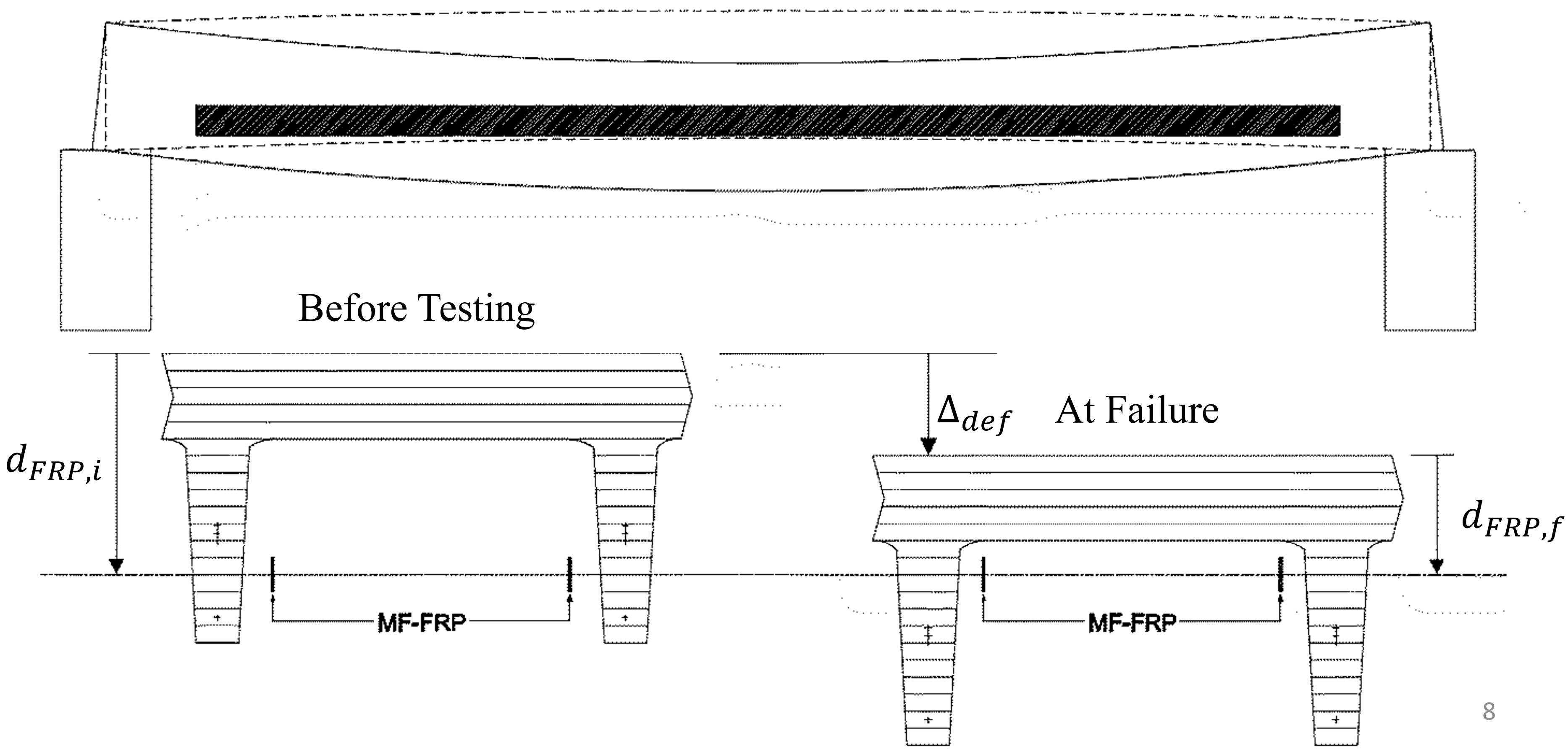
Curvature Profile

(3-point bending)



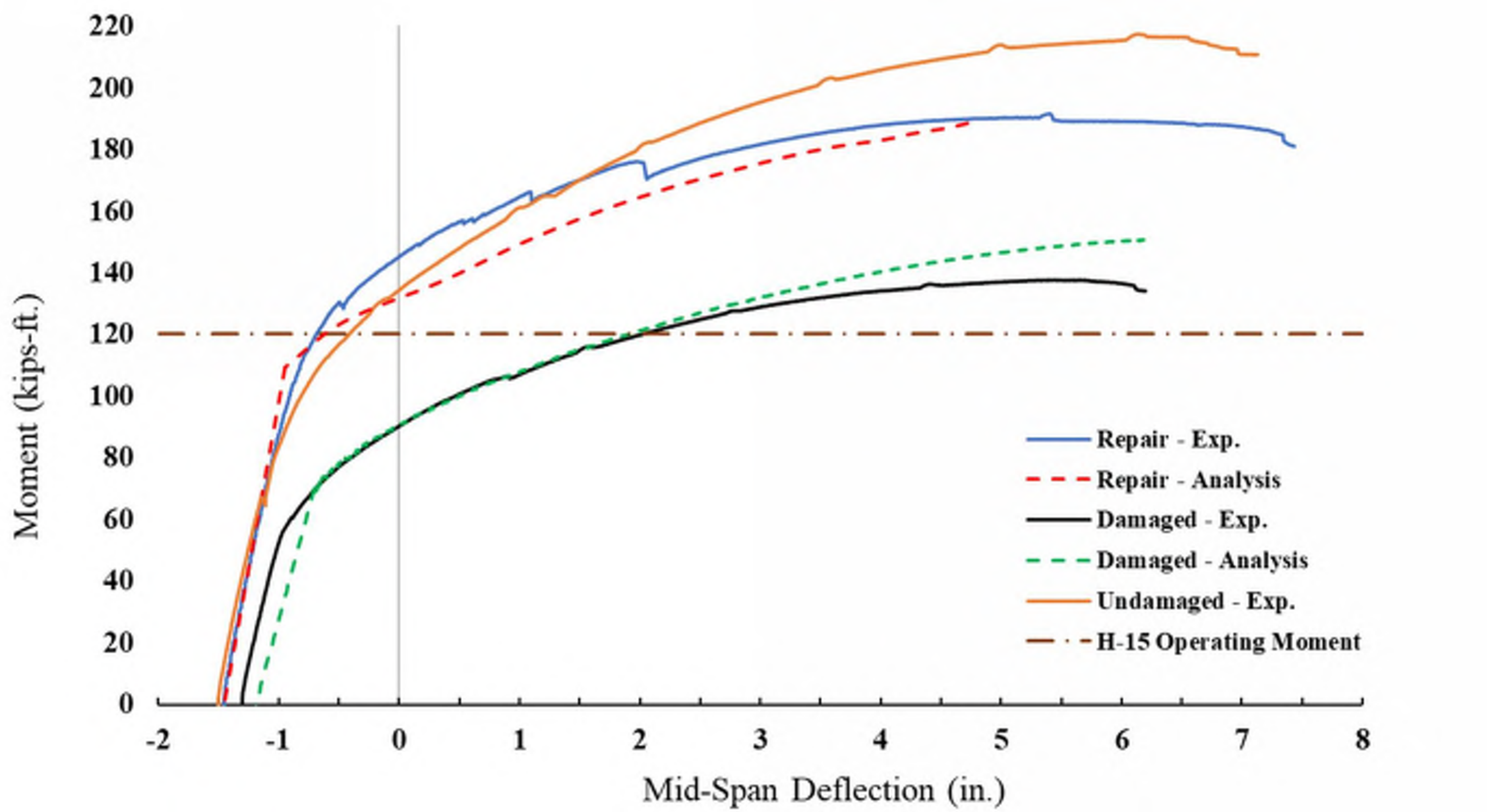
Predicted Global Behavior

- ❑ **Second-order effect**
  - ❑ MF-FRP system – similar to unbonded prestressing
  - ❑ No strain compatibility
  - ❑ Change in unbonded prestress force is related to member deflection



Predicted Global Behavior

- ❑ **Predicted vs Experimental Results**



Field Demonstration

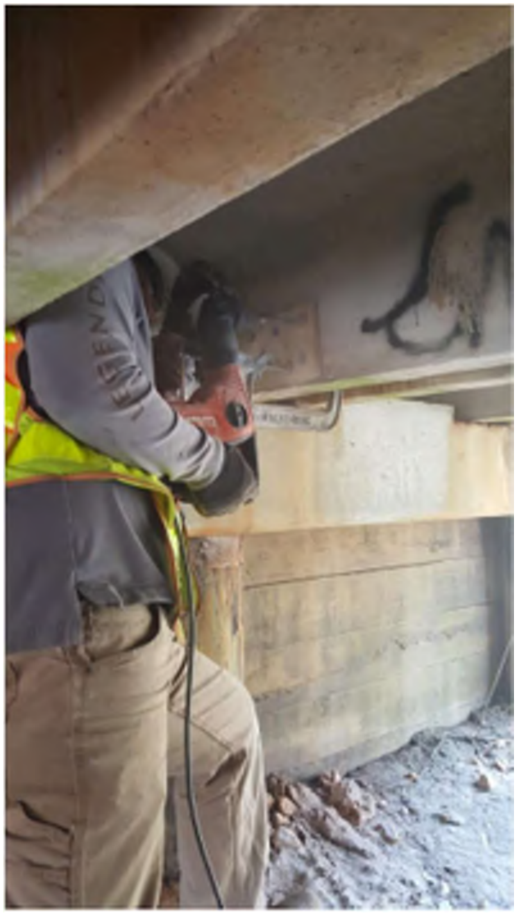
Bridge No. 340080, **Franklin County**, North Carolina – April 2019

- ❑ Built in 1961
- ❑ Previously repaired with patches
- ❑ Current posting 21/28

- ❑ Spalling and flexural crack of previous repair
- ❑ Requires posting 18/24 without repair
- ❑ ADTT ~50, impacting local logging industry

Field Demonstration

Bridge No. 340080, **Franklin County**, North Carolina – April 2019



- ❑ Rapid and easy installation
- ❑ Low material cost
- ❑ Installed by a four-person DOT crew
- ❑ Approximately 4.1 labor-hours for a single C-Channel beam repair installation

Field Demonstration

Bridge No. 340080, **Franklin County**, North Carolina – October 2020

- After 18 months of service:
  - retrofit remains in good condition
  - C-Channel beams are continuing to degrade

Field Demonstration

Bridge No. 810003, **Sampson County**, North Carolina – October 2020

- ❑ Built in 1966
- ❑ 3-span, C-channel beam
- ❑ Currently closed to traffic
- ❑ Previous posting 16/22

- ❑ Extensive spalling and flexural cracking of previous repairs
- ❑ Significant corrosion of prestressing strands
- ❑ ADTT ~60, Detour length 6 miles

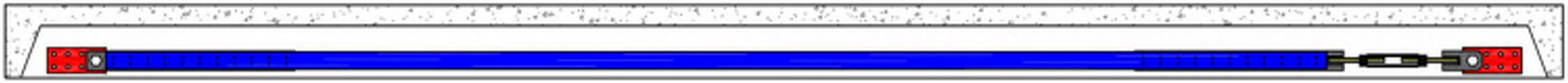
Field Demonstration

Bridge No. 810003, **Sampson County**, North Carolina – October 2020

Field Demonstration

Bridge No. 810003, **Sampson County**, North Carolina – Oct 2020

- **Retrofit Design – Flexural and Shear Strengthening**
- *Flexural Strengthening* – **MF-FRP 2.0 Design**
- *Shear Strengthening* – Apply **bolted steel plates** on the damaged stems in the end regions



Flexural Strengthening

Flexural and Shear Strengthening

Conclusions

- The proposed MF-FRP system addresses both inventory and operating load limits for prestressed concrete bridge beams.
- A procedure has been developed to predict the moment-displacement response of MF-FRP strengthened C-channel beams.
- An MF-FRP system remains in good condition on an existing bridge after 18 months of service since the installation.
- The MF-FRP design is optimized for rapid installation by a four-person DOT crew, without the need for specialized tools or equipment, that is an economical alternative compared to other options.
- A second repair on a closed C-Channel bridge is designed that addressed both flexural and shear strengthening.

Center for Integration of Composites into Infrastructure

- Acknowledgments:
  - Brad C. McCoy, Ph.D.: Assistant Professor, United States Military Academy
  - Zakariya Bourara, MS: Structural Engineer, Dewberry
  - Juliet Swinea, Senior Undergraduate, NCSU Civil Engineering Department

Prestressing with GFRP Bars and Strands

NCHRP-IDEA/207: MILDGLASS

Marco Rossini

Antonio Nanni

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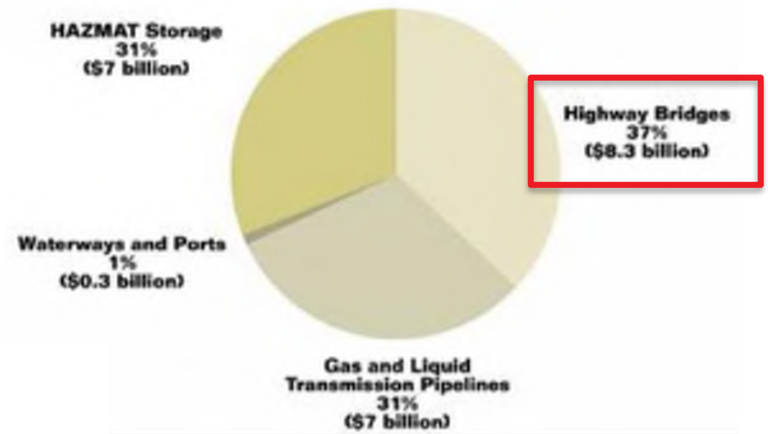
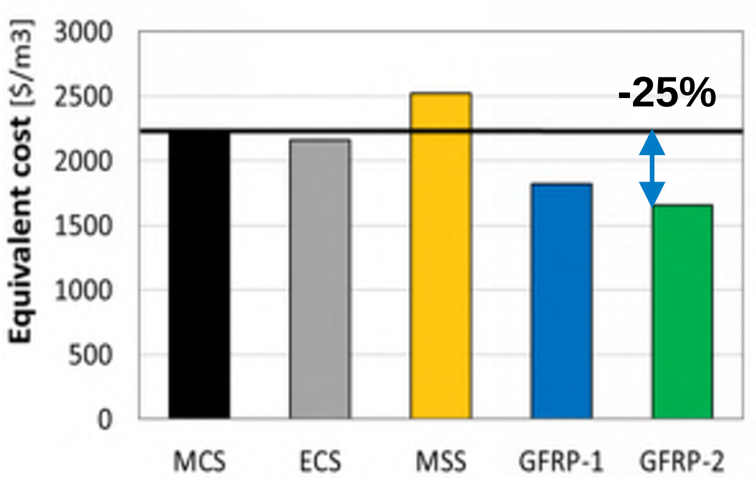
The Problem of Corrosion: Cost

- Demand for durable and low-maintenance technologies from: **DOTs, FHWA, AASHTO, EU** and member states
- **8.3B USD** annual cost of corrosion for highway bridges in the US
- **21B USD** total maintenance, rehabilitation, replacement cost for sheet piles in Florida (**3,600 miles** armored shoreline)
- Non-corrosive reinforcement may reduce Life Cycle Costs by **25%**





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Nolan, S., **Rossini, M.**, & Nanni, A. (2018). Seawalls, SEACON, and Sustainability in the Sunshine State
Nolan, S., & Nanni, A. (2017). Deployment of Composite Reinforcing
Rossini, M., Nanni, A., Matta, F., Nolan, S., Potter, W., & Hess, D. (2019). Overview of AASHTO Design Specifications for GFRP-RC Bridges 2nd Edition: Toledo Bridge as Case Study

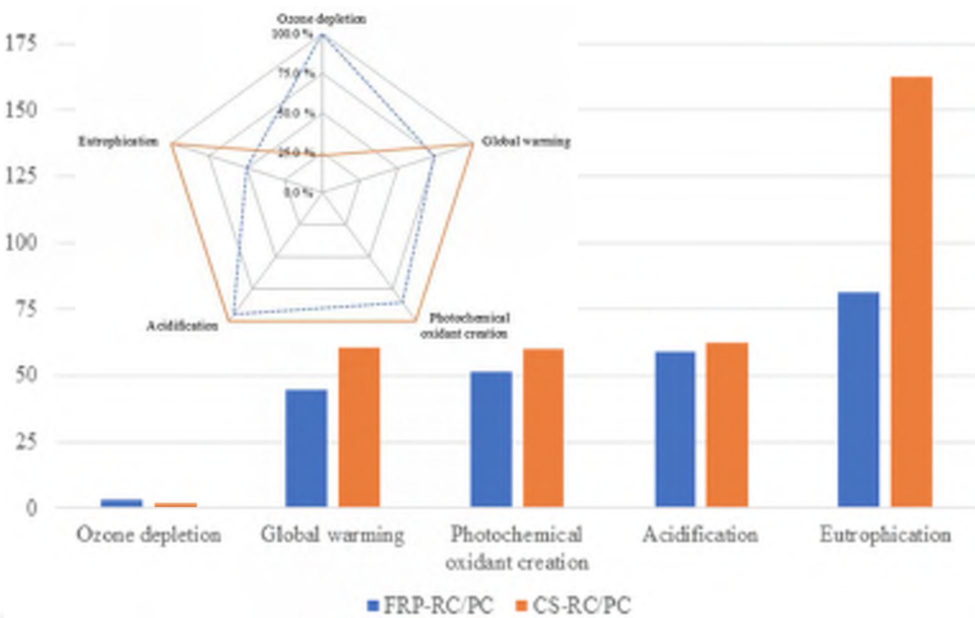
The Problem of Corrosion: Safety

- **10+ major Bridge Collapses** co-caused by corrosion since 2014
- Pre/Post-tensioned cable-stayed bridge in Genova (IT)
- Post-tensioned medium-span bridge in Agrigento (IT)

Bazzucchi, F., Restuccia, L., & Ferro, G. A. (2018). Considerations over the Italian road bridge infrastructure safety after the Polcevera viaduct collapse: Past errors and future perspectives

The problem of Corrosion: Sustainability & Resilience

- **Recyclability** applies to disposables
- **Durability** applies to structures and infrastructures
- Reduced environ. impact from maintenance (average **-25%**)
- Ensure **Resilience** of transportation network and communities



Cadenazzi, T., Dotelli, G., **Rossini, M.**, Nolan, S., & Nanni, A. (2019). Life-Cycle Cost and Life-Cycle Assessment Analysis at the Design Stage of a Fiber-Reinforced Polymer-Reinforced Concrete Bridge in Florida.

Solution: Fiber Reinforced Polymers

- CFRP strands for **prestress**
  - 1x7-15.2 mm
  - 2300 MPa | 155 GPa
  - **x4.0** times steel cost
- GFRP bars for **reinforcement**
  - 16 mm round solid
  - 800 MPa | 45 GPa
  - **x1.5** times steel cost
- GFRP strands for **mild PC (?)**

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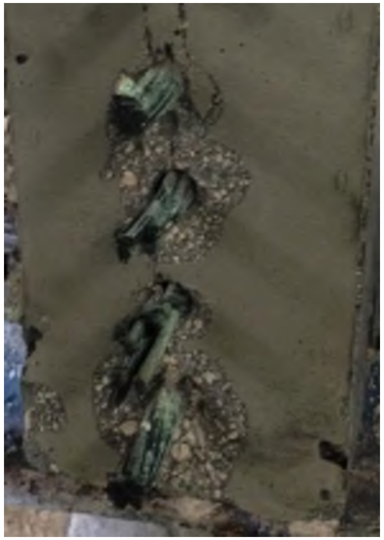
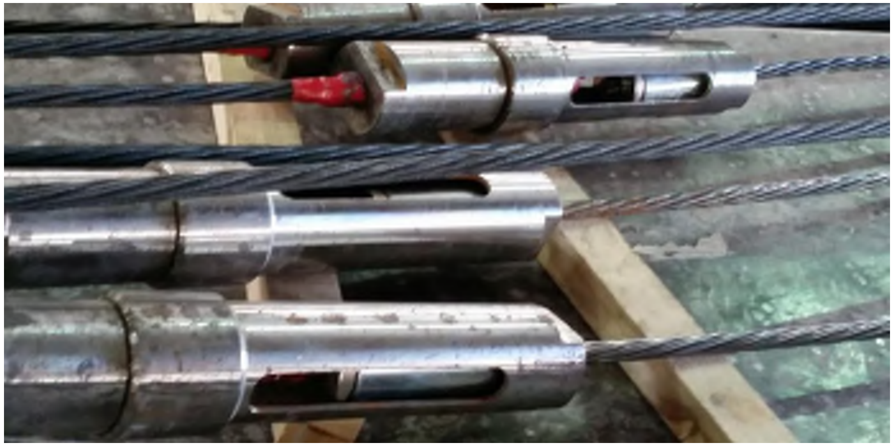
Challenges of CFRP Prestressing

- **Effective but complex**
- **Expensive: 4 times** steel
- **Expansive**: pseudo-Poisson ratio
- **Complex:** large anchors & splicing
- **Brittle:** constructability & safety


Concept: FRP Mild Prestressing

- **Low prestress level**

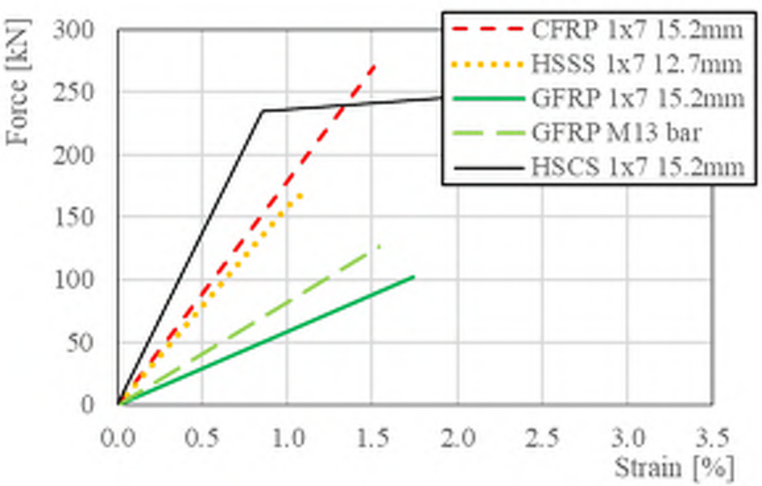
- **Simple**: standard anchors
- Steel-like **constructability**
- Limits cracking
- Safe pulling

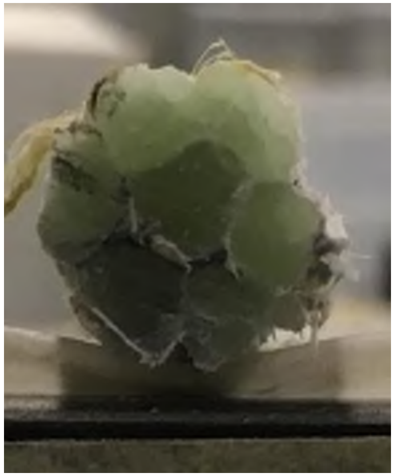
- Targets **Coastal Structures**

- **Highest corrosion**
- Lowest prestress
- Piles, sheet piles, seawalls

Prototype: GFRP Strand

- **Tailored for deployment**
- **Economic:** **1.5 times** steel
- **Efficient:** low modulus → **low losses**
- **Simple:** same anchors as steel-PC
- **Pseudo-ductility:** large displacement





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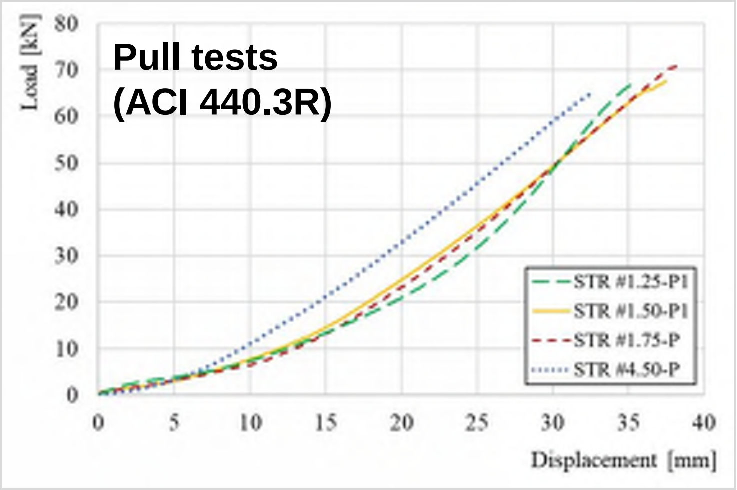
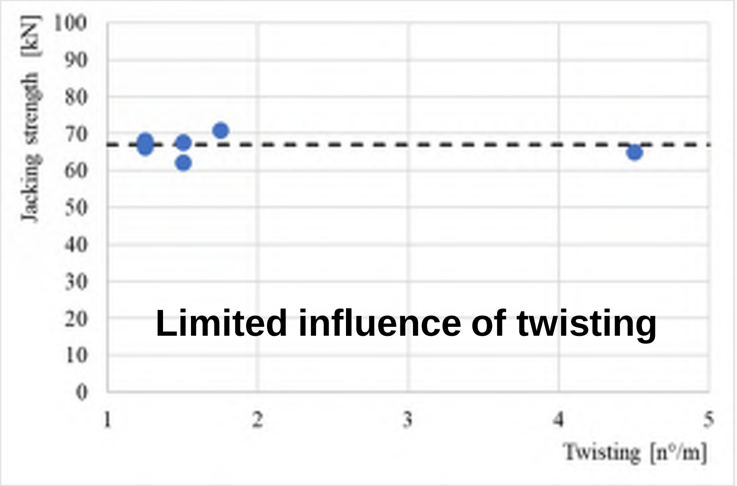
Pull Strength with Steel-PC Anchors

- <u>**Standard anchors**</u> and wedges
- **7 tests** | COV = 3.9%
- <u>**Guaranteed**</u> **56% GTS**

  464 MPa

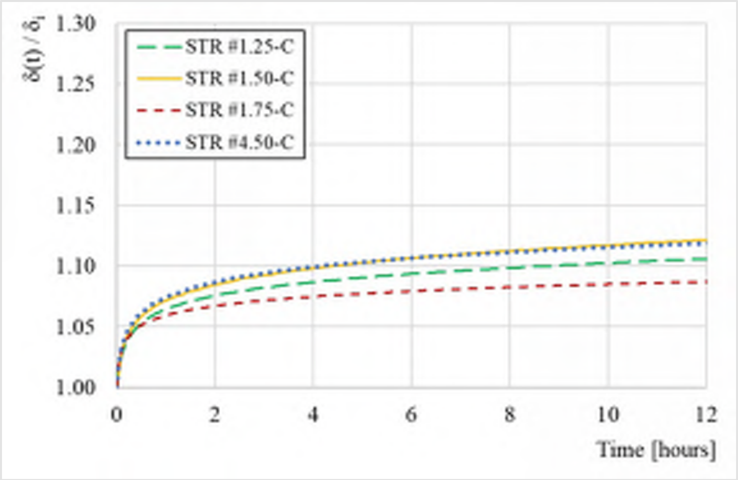
  59 kN

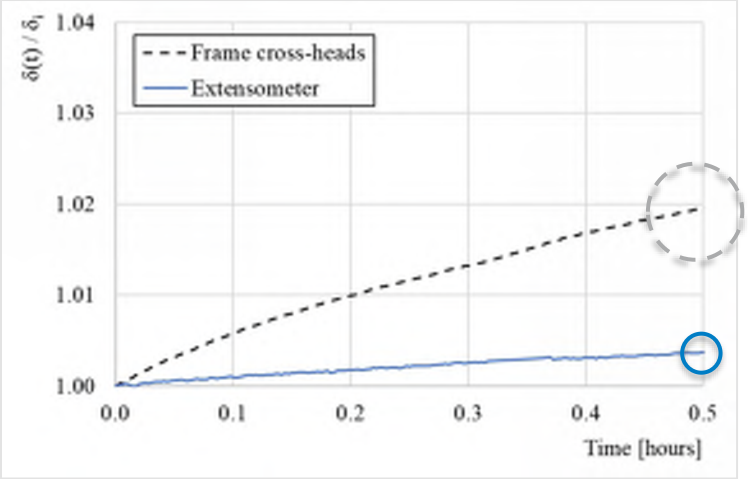




Pseudo-creep Behavior

- **Load control**
- $\delta/\delta_i = 1.11$ | COV = 1.2%
- **20% creep** in the strand
- **80% slip** at anchors
  - As the anchors slip and the strand creeps, the crossheads move to apply more load
  - The extensometer only sees creep
- Slip → **setting losses**





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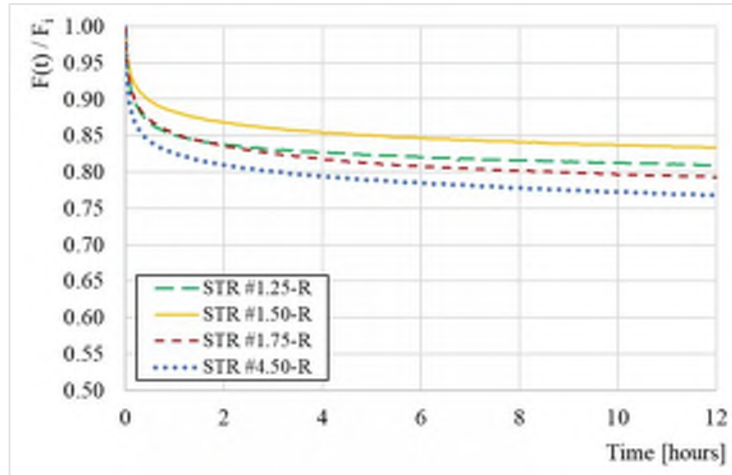
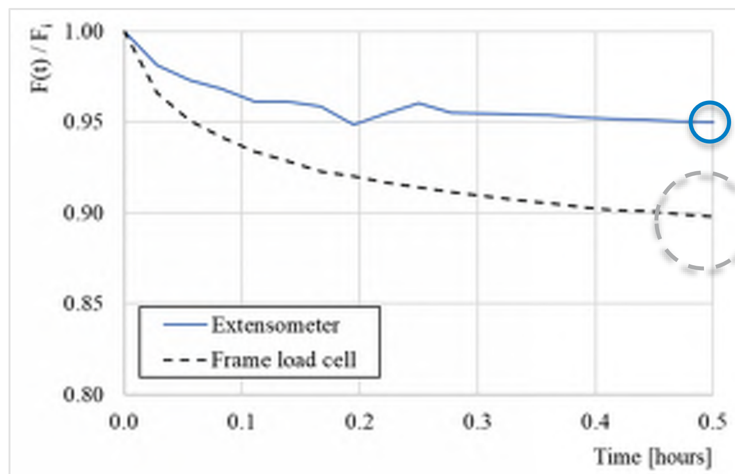
Pseudo-relaxation Behavior

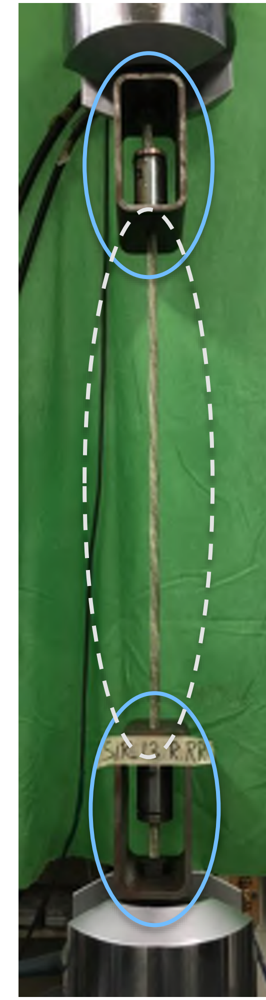
- **Displacement control**
- $\Delta F = 0.20\ F_i$ | COV = 12%
- **50% relax.** in the strand
- **50% slip** at anchors

  - No movement at crossheads
  - As the anchors slip, the strand shortens and the extensometer measures

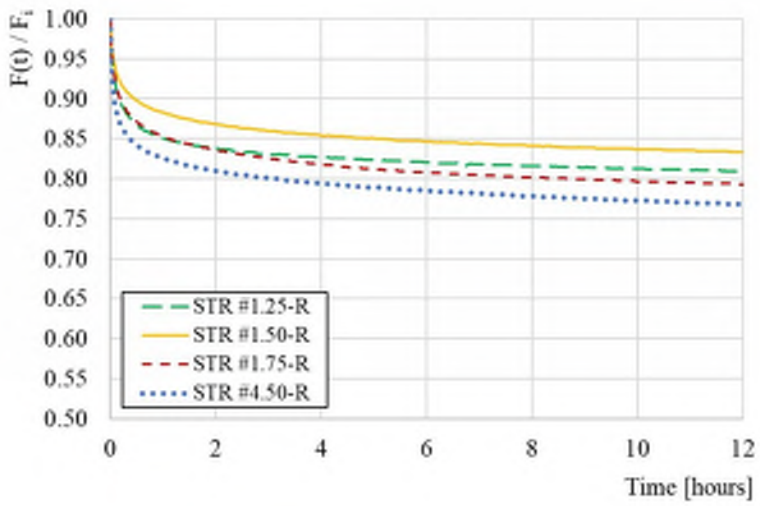
- Need to **reduce losses**







Pull Techniques for Reduced Losses

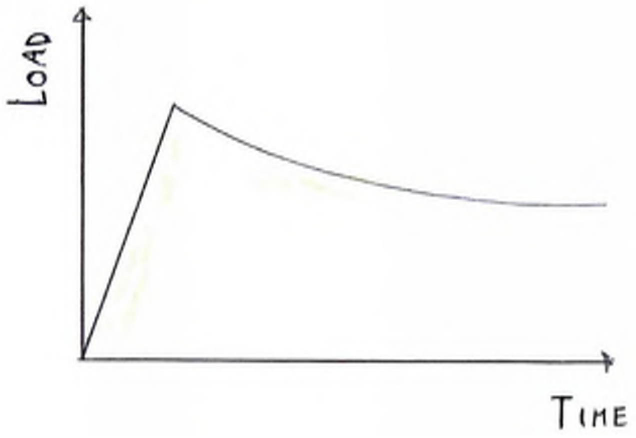


Single pull

0.20 F_i

Simple and familiar to precasters

Are **re-pull** or **pre-pull** necessary & feasible?



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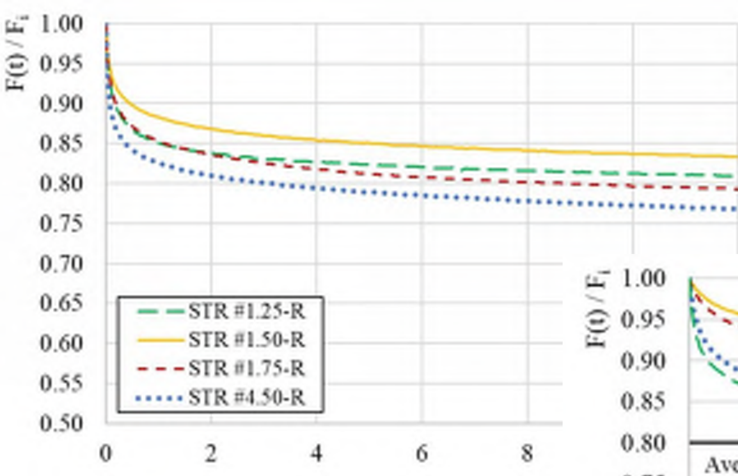
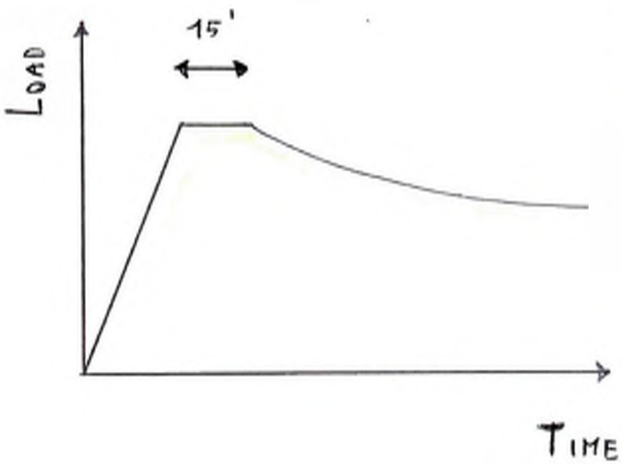
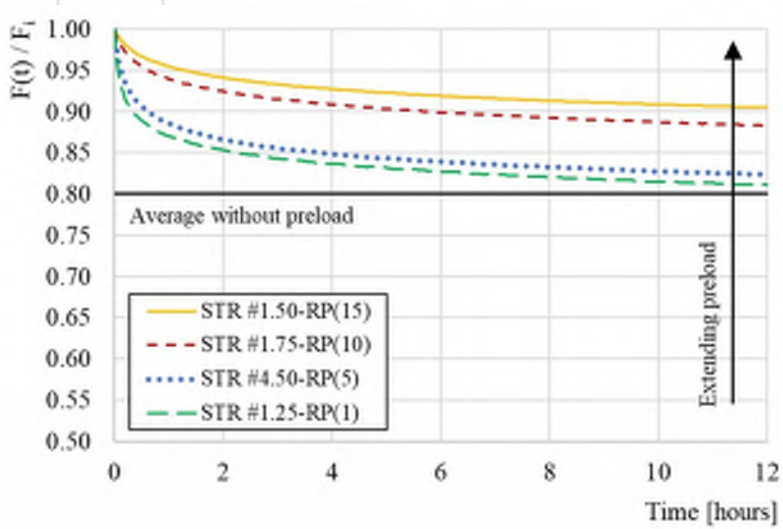




Pre-pull 1 to 15 minutes

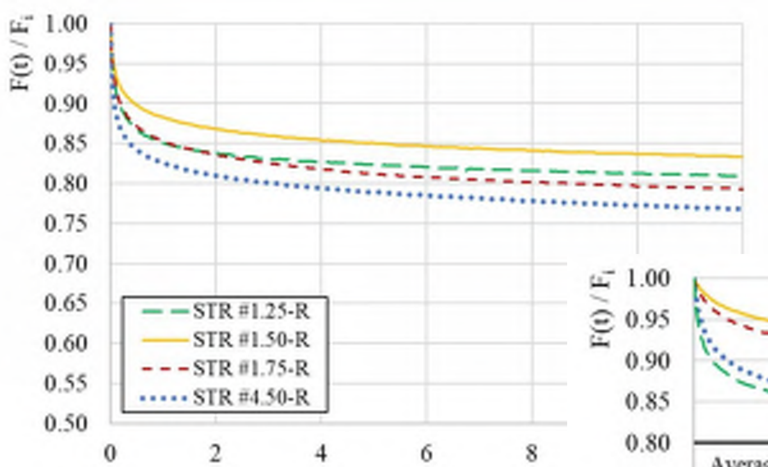
0.20 F_i → **0.10** F_i



Better performance

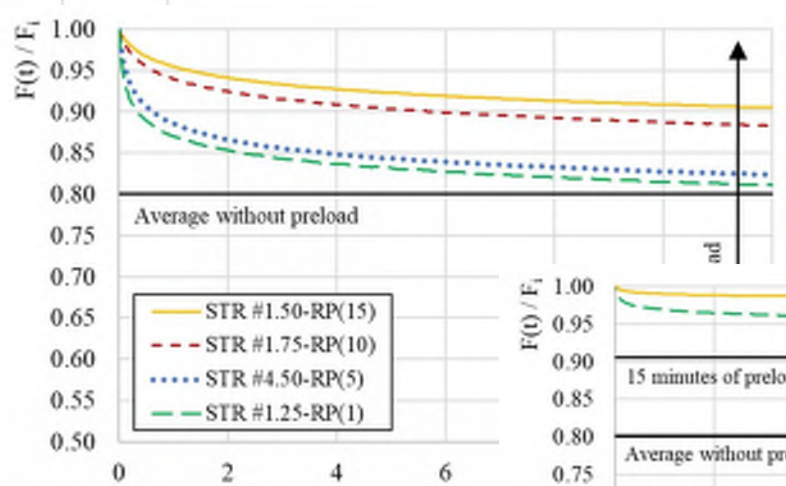
Difficult to deploy

Pull Techniques for Reduced Losses

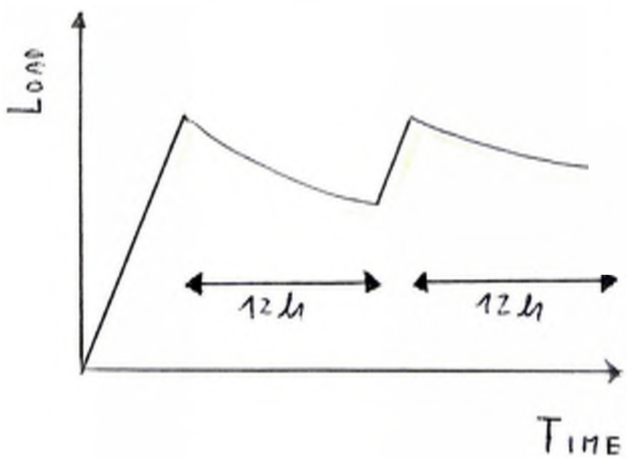


Re-pull after 12 hours

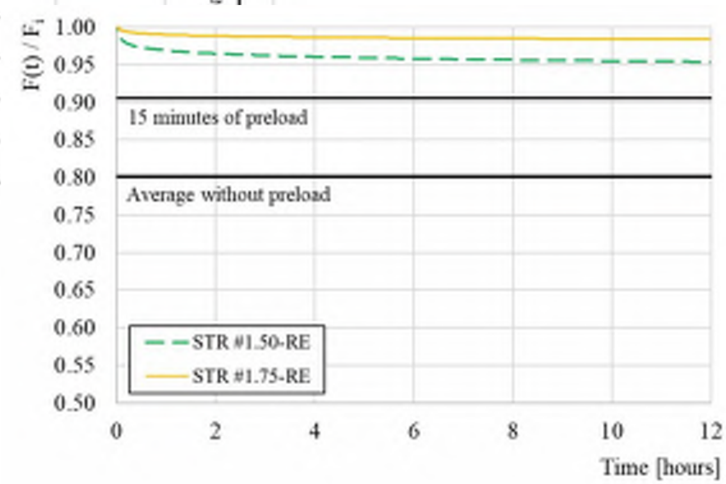
$0.20\ F_i \rightarrow 0.10\ F_i \rightarrow$ **0.04** F_i



Best performance



Typical for stress-relieved



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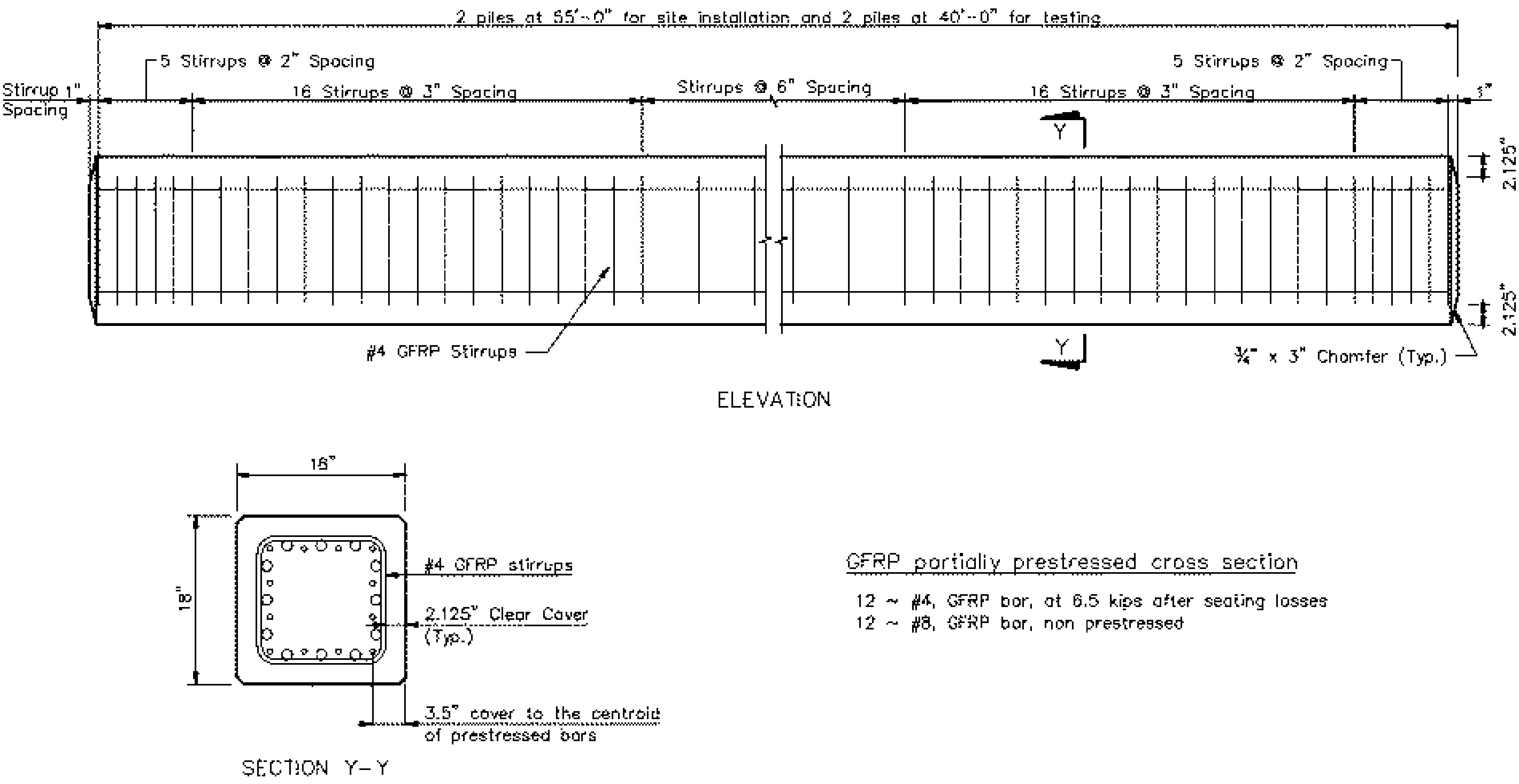
First GFRP-PC Piles in the Ground in Florida

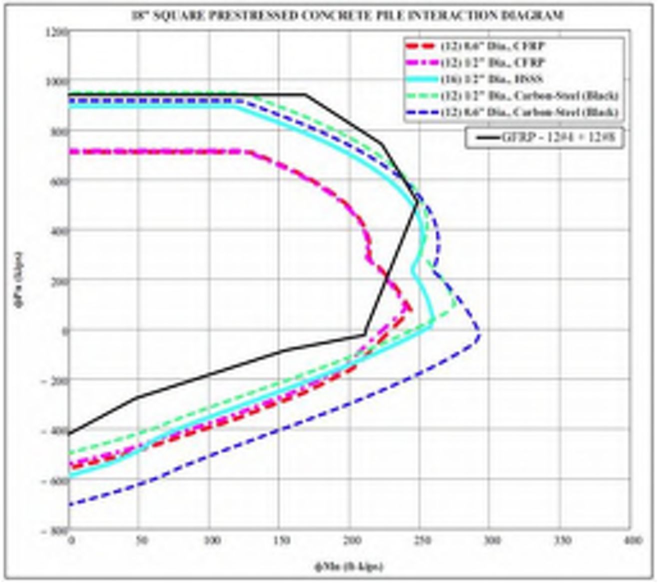
Installation at 23rd Avenue Bridge

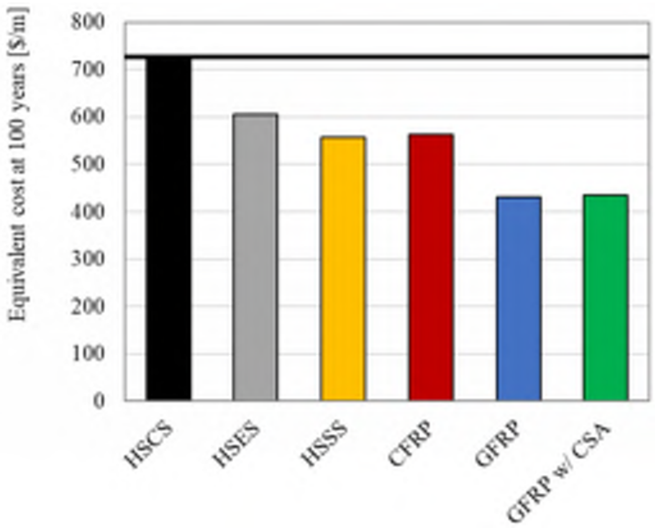
Shop Drawings per FDOT Specifications



Structural & Economic Performance

- **Partially prestressed**
  - **12 M13** at 30 kN (30% GTS)
  - **12 M25** non-prestressed
- **Same performance** as FDOT steel, stainless, CFRP design
  - **Flexure, shear, drivability**
- **40% cheaper** than steel and **25% cheaper** than carbon over its life cycle.
- **100 years** service life





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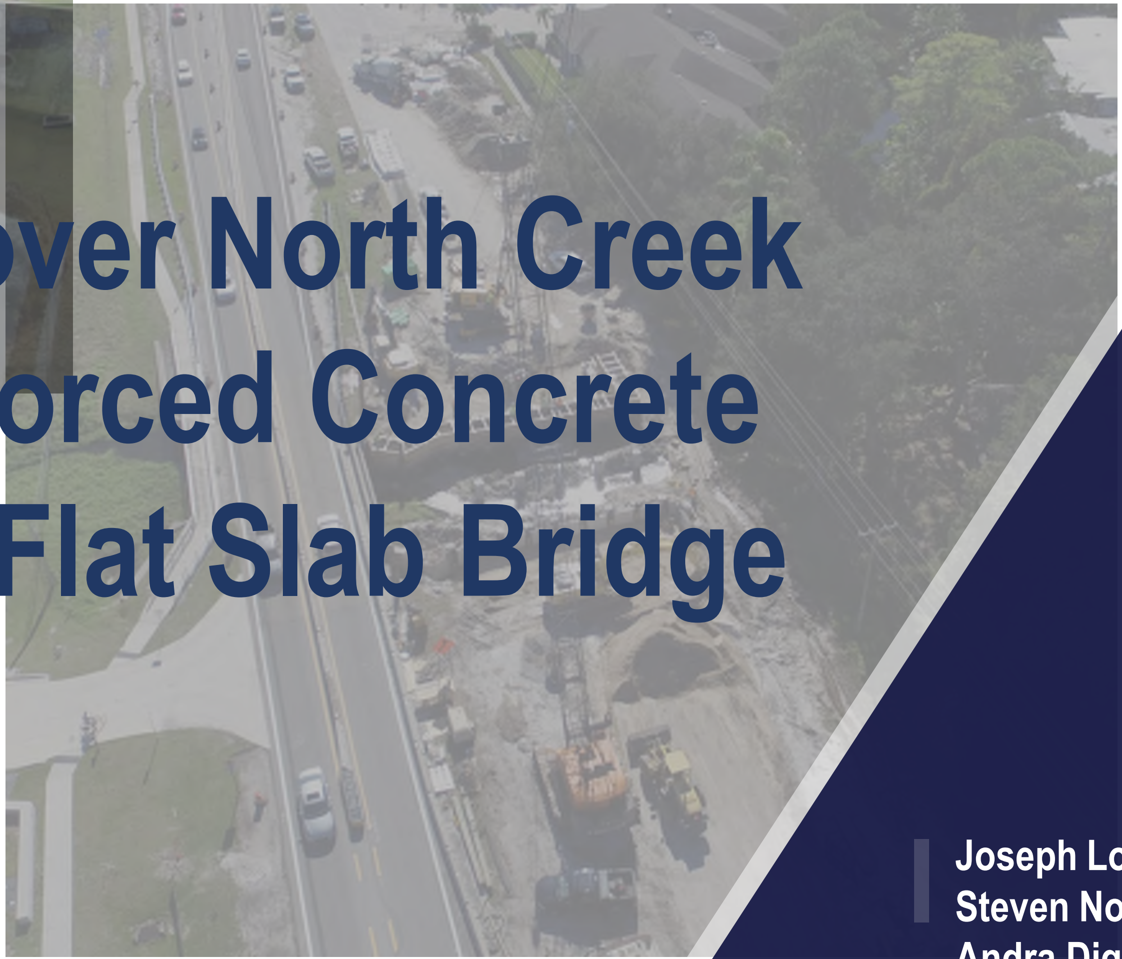
Conclusions

- Developed the concept of **Mild Prestressing**:
  - Mitigate challenges of CFRP in some applications
  - **GFRP strands prototype**
  - **Traditional steel-PC anchors**
- Feasible technology with pull at **30-50 %GTS**
- **First demonstrator** successfully installed at 23rd Avenue Bridge a Florida DOT project.
- Same performance, more **durable**, at a **lower cost**.

Question?

Thank U !

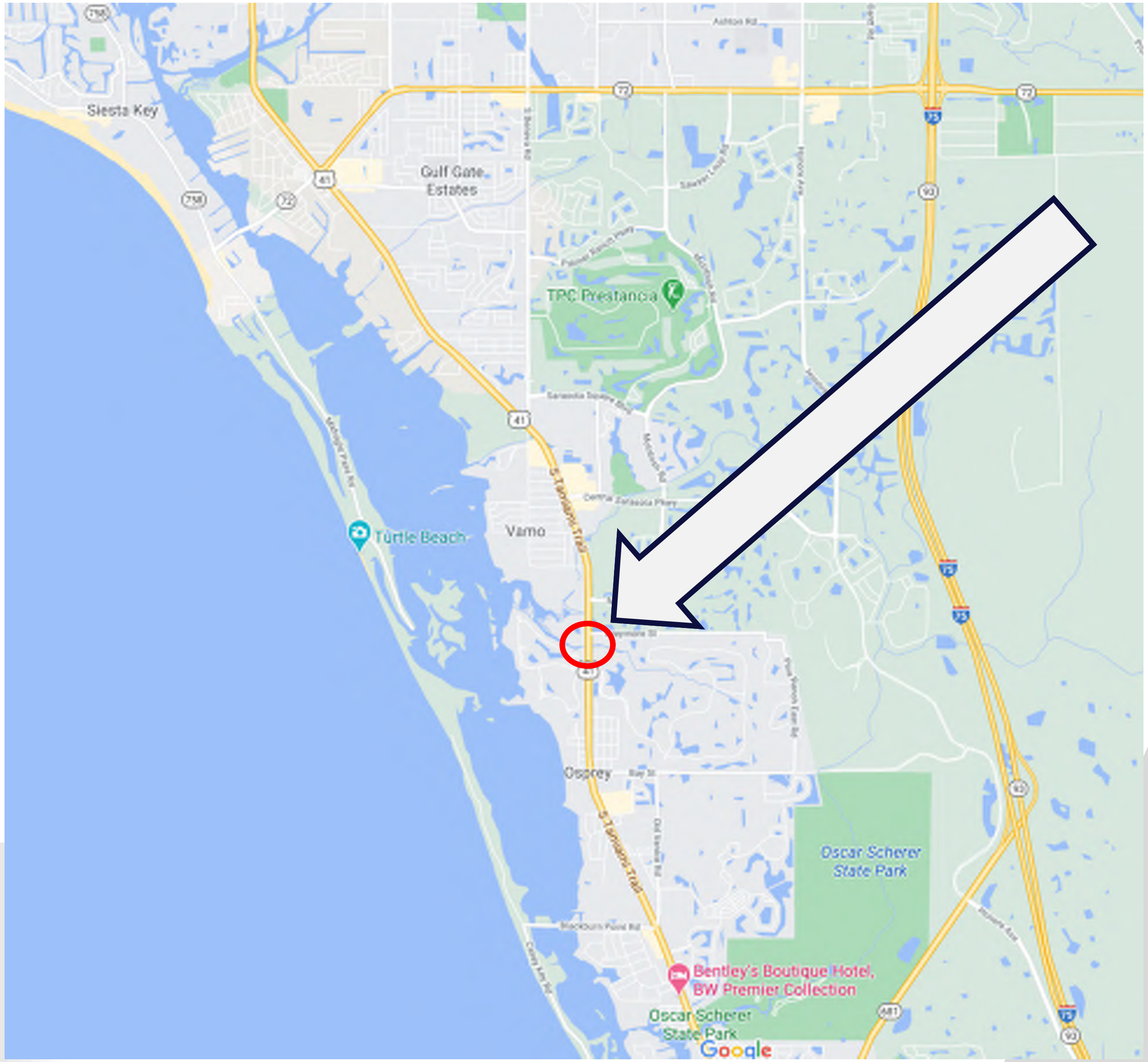


US 41 NB over North Creek FRP Reinforced Concrete Two-Span Flat Slab Bridge

Joseph Losaria, PE - PGA
Steven Nolan, PE - FDOT
Andra Diggs II, PE - FDOT
David Hartman – Owens Corning

PROJECT LOCATION

- Sarasota County, Florida
- South of Sarasota, FL near Osprey, FL
- Outfalls to Little Sarasota Bay
- Tidally Influenced
- Within FDOT District 1

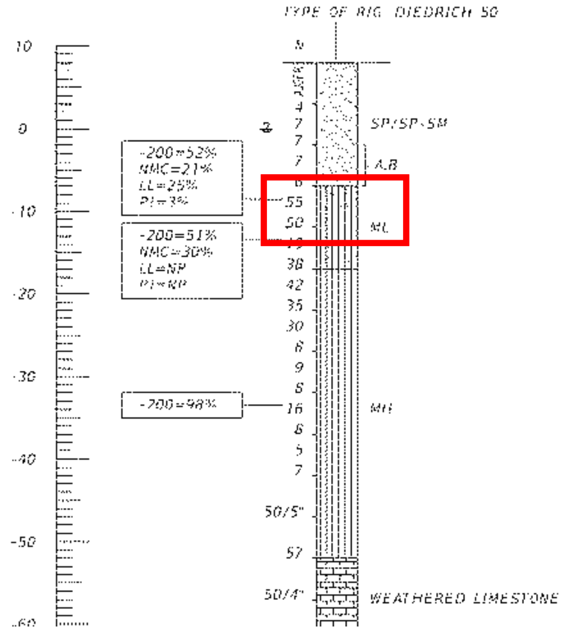


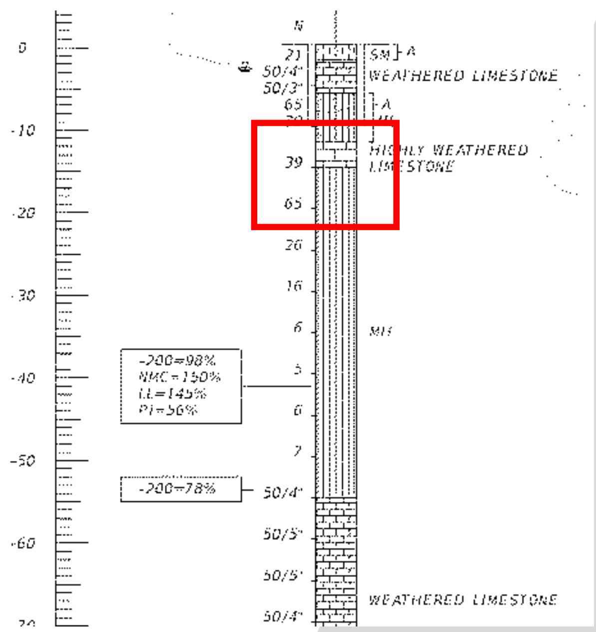
INTRODUCTION

- **FLORIDA DEPARTMENT OF TRANSPORTATION (FDOT) PROJECT**
  - **Transportation Innovation Challenge Initiative (Andra Diggs II)**
  - **Project required additional shoulder, bike lanes and sidewalk**
  - **Existing Bridge**
    - Built in 1927 and widened in 1950
    - No existing plans available
    - Existing bridges were cast in place flat slab superstructures on unknown foundations
    - Utilized vertical wall abutment
    - Previous pile jacket repairs
  - **Bridge widening was considered but was not feasible given the age of the bridge.**
  - **Options considered during bridge development study:**
    - Separate shared use path bridge
    - Bridge replacement
    - Culvert alternative

GEOTECHNICAL

- **Presence of shallow limestone layer**
- **Extremely aggressive environment**
  - Tidal Condition at North Creek
  - Flows to Little Sarasota Bay
- **Foundation options considered:**
  - Steel Piles
  - Precast Square Concrete Piles
  - Drilled Shafts

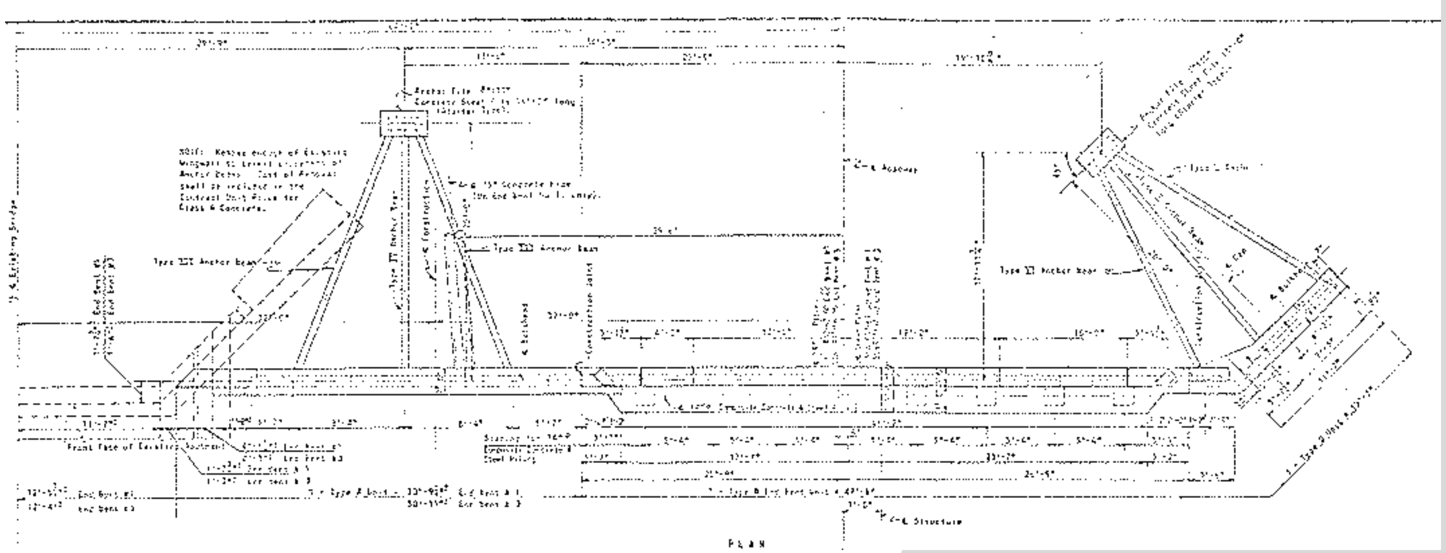




END BENT SYSTEM

- Need vertical retaining walls at abutments to tie into SB bridge that is to remain

- Existing abutment wall system:
  - Concrete sheet pile walls with a deadman system



END BENT SYSTEM

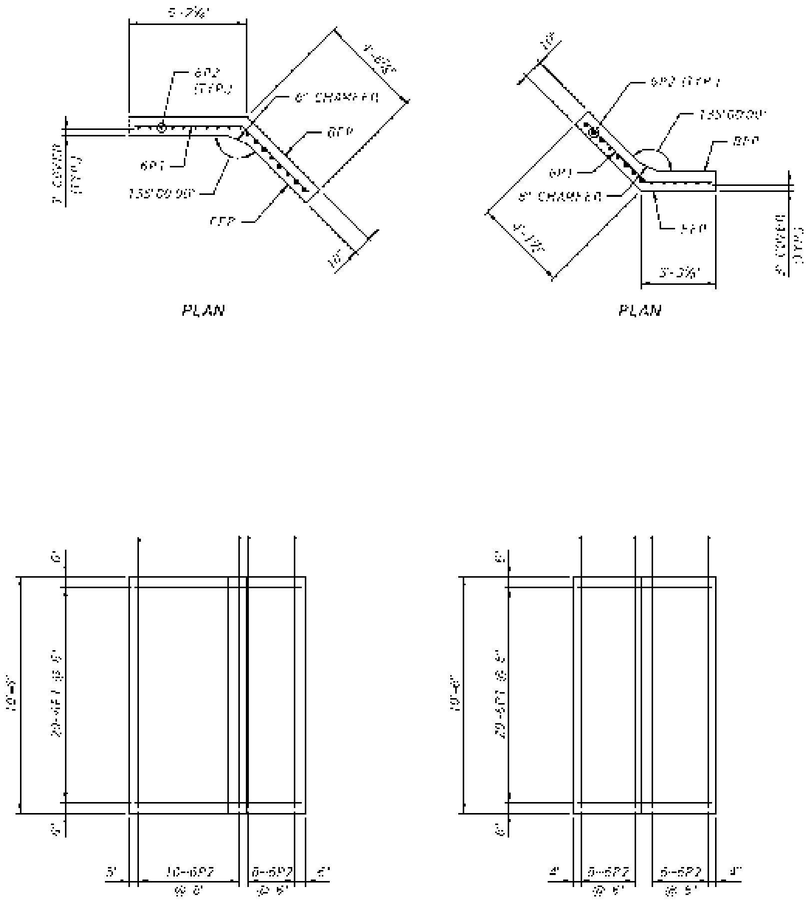
- **Evaluated several retaining wall types**
  - **Steel sheet pile**
    - Issue with shallow limerock layer
  - **Concrete sheet pile with deadman system**
    - Costly and labor intensive
  - **Soldier-Pile wall**
    - Uses precast square concrete piles
    - Uses precast concrete panels
- **Recommendation: Concrete Soldier Pile Wall System**

END BENT SYSTEM

- **Recommendation: Concrete Soldier Pile Wall System**

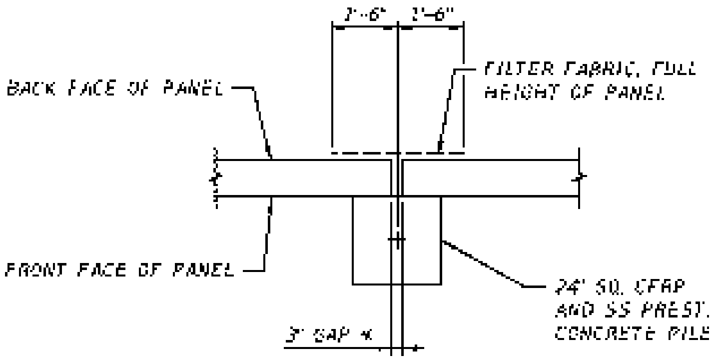
END BENT SYSTEM

- **Precast Concrete Panels**
  - Able to accommodate geometry changes along wall.
  - Faster construction since panels are precast.



END BENT SYSTEM

- **Precast Concrete Panels**



* CONTRACTOR SHALL GROUT THE GAP BETWEEN ADJACENT PANELS IN ACCORDANCE WITH SPEC. 451-4.5. GROUT SHALL PROVIDE FULL BEARING OF PANEL AGAINST PILE AND COMPLETELY SEAL ANY OPENINGS BETWEEN PANELS AND CONCRETE PILES. PRIOR TO GROUTING, THE VERTICAL JOINTS BETWEEN PANELS SHALL BE CLEANED AND FREE OF DEBRIS.

PRECAST CONCRETE PANEL GAP DETAIL

END BENT SYSTEM

- **Lateral Stability**
  - Need to check at service and during construction limit state
  - Control deflections at top of pile until pile cap is poured

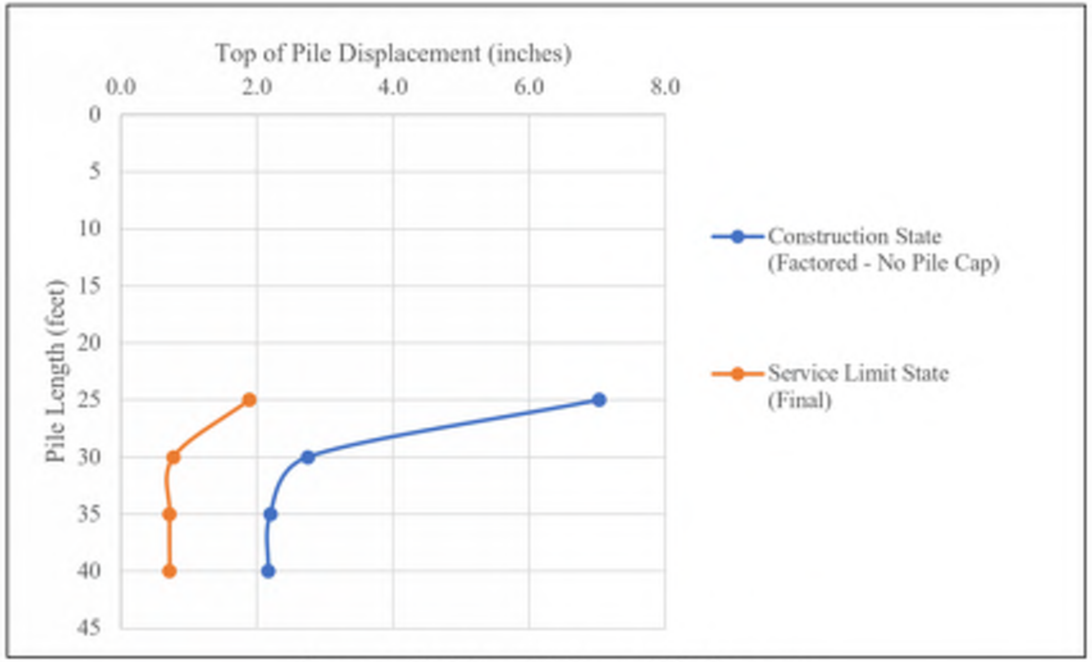


Figure 3 – End Bent Pile Lateral Displacement

END BENT SYSTEM

- **FRP Materials:**
  - Utilized CFRP/SS strands for prestressed piles
  - Utilized GFRP reinforcement for precast panels
- **Benefits:**
  - No corrosion in extremely aggressive environment
  - Easier handling during precast construction
- **Challenges:**
  - Contractor had to handle top hooked bars with care
  - Procurement time for GFRP bars are longer

END BENT SYSTEM

- **Unique Items:**
  - Similar bridge one-mile north of North Creek replaced last year with conventional materials
  - Will compare performance of FRP versus conventional materials
  - FRP test panels were provided with additional GFRP reinforcing
  - Utilized carbon black steel on bent caps for constructability and field adjustability

SUPERSTRUCTURE

- CIP Concrete Flat Slab Superstructure
- Utilized GFRP Bars
- Design was completed using AASHTO LRFD Bridge Design Guide Specifications for GFRP Reinforced Concrete Bridge Decks and Traffic Railings, 1st Edition

SUPERSTRUCTURE

- **Effect of incorporating newer design criteria**

GFRP Design Value (1st Edition)	GFRP Design Value (2nd Edition)
Moment Flexural Resistance = 148 kip-ft (201 kN-m)	Moment Flexural Resistance = 172 kip-ft (233 kN-m)
Fatigue Limit Maximum Stress = 11.9 ksi (82 MPa)	Fatigue Limit Maximum Stress = 14.9 ksi (103 MPa)
Positive Sustained Tensile Stress in GFRP = 13.5 ksi (93 MPa)	Positive Sustained Tensile Stress in GFRP = 6.9 ksi (48 MPa)
Negative Sustained Tensile Stress in GFRP = 12.9 ksi (89 MPa)	Negative Sustained Tensile Stress in GFRP = 7.66 ksi (53 MPa)

SUPERSTRUCTURE

- **Summary of changes from 1st edition and 2nd edition of AASHTO**

Design Factor	AASHTO (2nd Edition)	AASHTO (1st Edition)	ACI 440.1R-15	CSA (2014)	Critical Design Parameter Description
f_{fu}^*	99.9	99.9	99.9	95.0	Strength percentile
Φ_C	0.75	0.65	0.65	0.75	Resistance factor concrete failure
Φ_T	0.55	0.55	0.55	0.55	Resistance factor FRP failure
Φ_S	0.75	0.75	0.75	0.75	Resistance factor shear failure
C_E	0.70	0.70	0.70	1.0	Environmental reduction
C_C	0.30	0.20	0.20	0.25*	Creep rupture reduction (* C_E not applied)
C_f	0.25	0.20	0.20	0.25*	Fatigue reduction (* C_E not applied)
C_b	0.83	0.70	0.70	1.0	Bond reduction
w	0.028 (0.7)	0.02 (0.5)	0.028 - 0.020 (0.7 - 0.5)	0.02 (0.5)	Crack width limit inch (mm)
$c_{c, stirrup}$	1.5 (40)	1.5 (40)	2.0 (50)	1.5 (40)	Clear cover inch (mm)
$c_{c, slab}$	1.0 (25)	0.79 (20) – 2.0 (50)	0.79 (20) – 2.0 (50)	1.5 (40)	Clear cover inch (mm)

BENEFITS OF FRP

- Addresses corrosion within the splash zone area
- Reduced concrete cover on GFRP reinforced components
- Easier handling and placement of FRP components
- Reduction in long-term maintenance costs
- Provides FDOT opportunity for material performance comparison

COST COMPARISON

- **Costs of FRP and Carbon Steel Soldier Pile End Bent Systems**

North Creek (FRP):	Quantity	Unit	Unit Cost	Total Cost
Concrete Class IV, Bulkhead (no C.I.) With GFRP Bars, #6	47.9 (36.6)	CY (m^3)	$ 1,067.20 ($1,395.03)	$ 51,118.90
24" CFRP SPC Piles (no HRP)	1386 (422.7)	LF (m)	$ 150.00 ($ 491.80)	$207,900.00
TOTAL BULKHEAD COST =				$259,018.90
Catfish Creek (Black Carbon Steel):	Quantity	Unit	Unit Cost	Total Cost
Concrete Class IV, Bulkhead (with C.I.) With #7 Reinforcing Steel	51.68 (39.51)	CY (m^3)	$ 1,131,53[1] ($ 1,479.12) [1]	$ 58,477.41
24" SPC Piles (with HRP)	1157.2 (352.9)	LF (m)	$ 106.00 [2] ($ 347.54[2])	$122,663.20
TOTAL BULKHEAD COST =				$181,140.61

Highly Reactive Pozzolan (HRP), Corrosion Inhibitor (CI)

COST COMPARISON

- **Costs of FRP and Carbon Steel CIP Flat Slab Superstructure**

North Creek (FRP):	Quantity	Unit	Unit Cost	Total Cost
Concrete Class IV, Bridge Superstructure (no C.I.) With GFRP Bars, #4, #8, #10	157.2 (120.3)	CY (m^3)	$ 1,836.40 ($2,400.53)	$ 288,682.75
Catfish Creek (Black Carbon Steel):	Quantity	Unit	Unit Cost	Total Cost
Concrete Class IV, Bridge Superstructure (with C.I.) (1) With #4, #5, #8 Reinforcing Steel	51.68 (39.51)	CY (m^3)	$ 1,552.75(1) ($ 1,479.12) (1)	$ 131,129.85

- **Bridge total length and span arrangement varied:**
  - North Creek = 58-ft total, 35-ft Span 1 and 23-ft Span 2
  - Catfish Creek = 40-ft total, 20-ft equal spans

COST COMPARISON

- **Cost Comparison Conclusions:**
  - Bridge with FRP has higher initial costs
  - 100-year service life for FRP reinforced structure versus 75-year service life for carbon steel reinforced structure
  - Payback period = 20 years
  - Including maintenance costs, LCC savings can be up to 50% for FRP reinforced structures

CONCLUSIONS (BENEFITS):

- FRP eliminates any corrosion concern particularly for elements within the splash zone
  - Benefits in urban environments with a tight R/W
- Ease of handling of GFRP reinforcement during construction
- Longer service life for FRP reinforced structure
- Use of soldier-pile wall end bent system with FRP materials provides highly durable bridge wall system in extremely aggressive environments
- Further refinements of design codes for FRP will bring further substantial cost savings

CONCLUSIONS (CHALLENGES):

- **Procurement of FRP materials was longer compared to traditional materials**
- **Handling of precast panels with exposed hooked FRP bars required careful handling**
- **Sand coating on GFRP reinforcement had challenges in handling for field crew**
  - Consideration for use of larger spacing between GFRP
- **Unforeseen existing bridge foundation locations**
  - No as-built plans available for existing bridge

QUESTIONS?

NORTH CAROLINA
Department of Transportation

Harkers Island Bridge Replacement

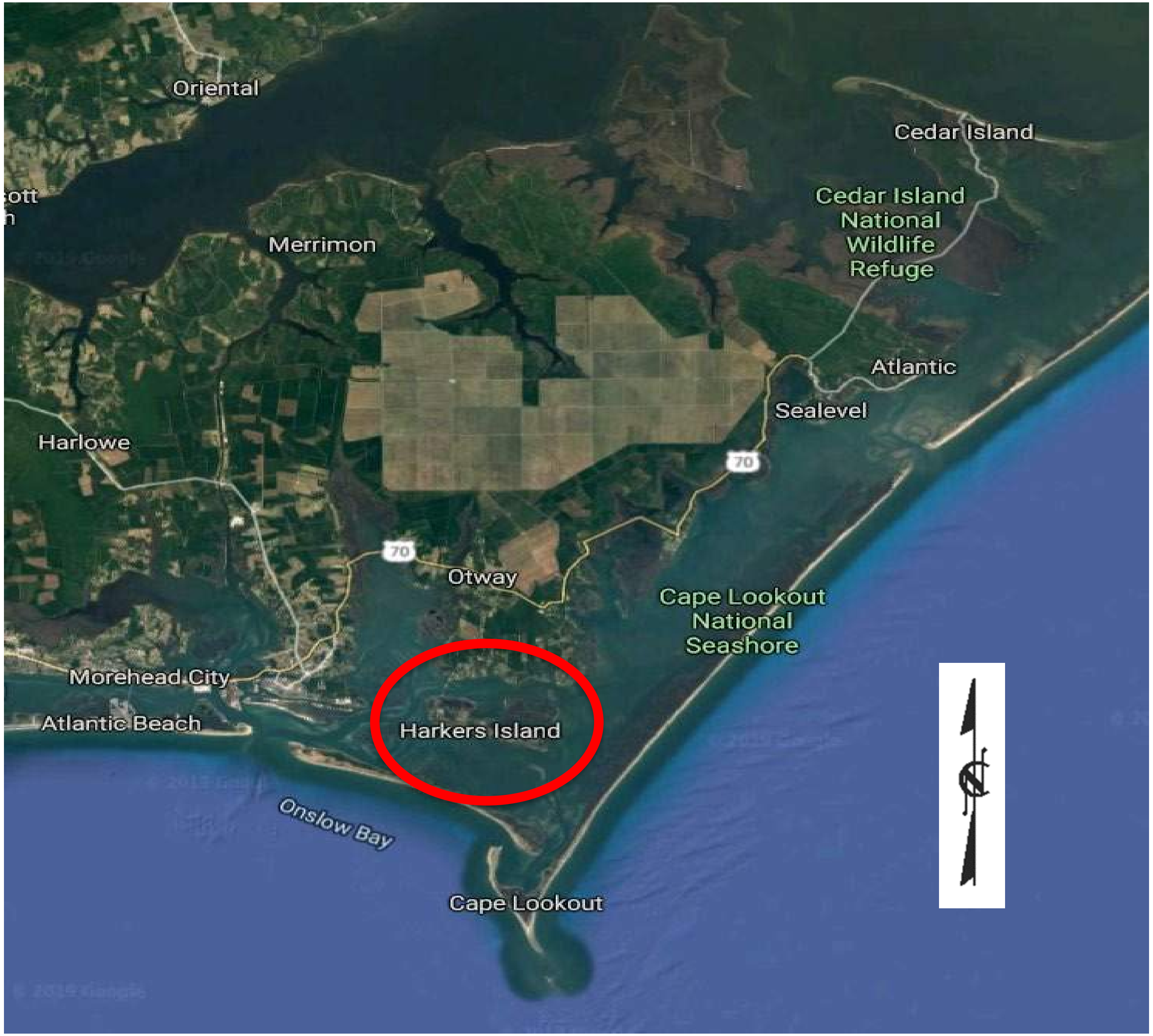
Trey Carroll, P.E.

October 27, 2020


85
Durham
40
Rocky Mount
Raleigh
Wilson
Greenville
Nags Head
95
40
Fayetteville
New Bern
Jacksonville
Morehead City
Wilmington
Conway


Durham
Rocky Mount
Nags Head
Raleigh
Wilson
Greenville
Fayetteville
New Bern
Jacksonville
Morehead City
Wilmington
Conway
85
40
95
40


Oriental
Cedar Island
Cedar Island National Wildlife Refuge
Merrimon
Atlantic
Sealevel
Harlowe
70
70
Otway
Cape Lookout National Seashore
Morehead City
Atlantic Beach
Harkers Island
Onslow Bay
Cape Lookout
N


Oriental
Cedar Island
Cedar Island National Wildlife Refuge
Merrimon
Atlantic
Sealevel
Harlowe
70
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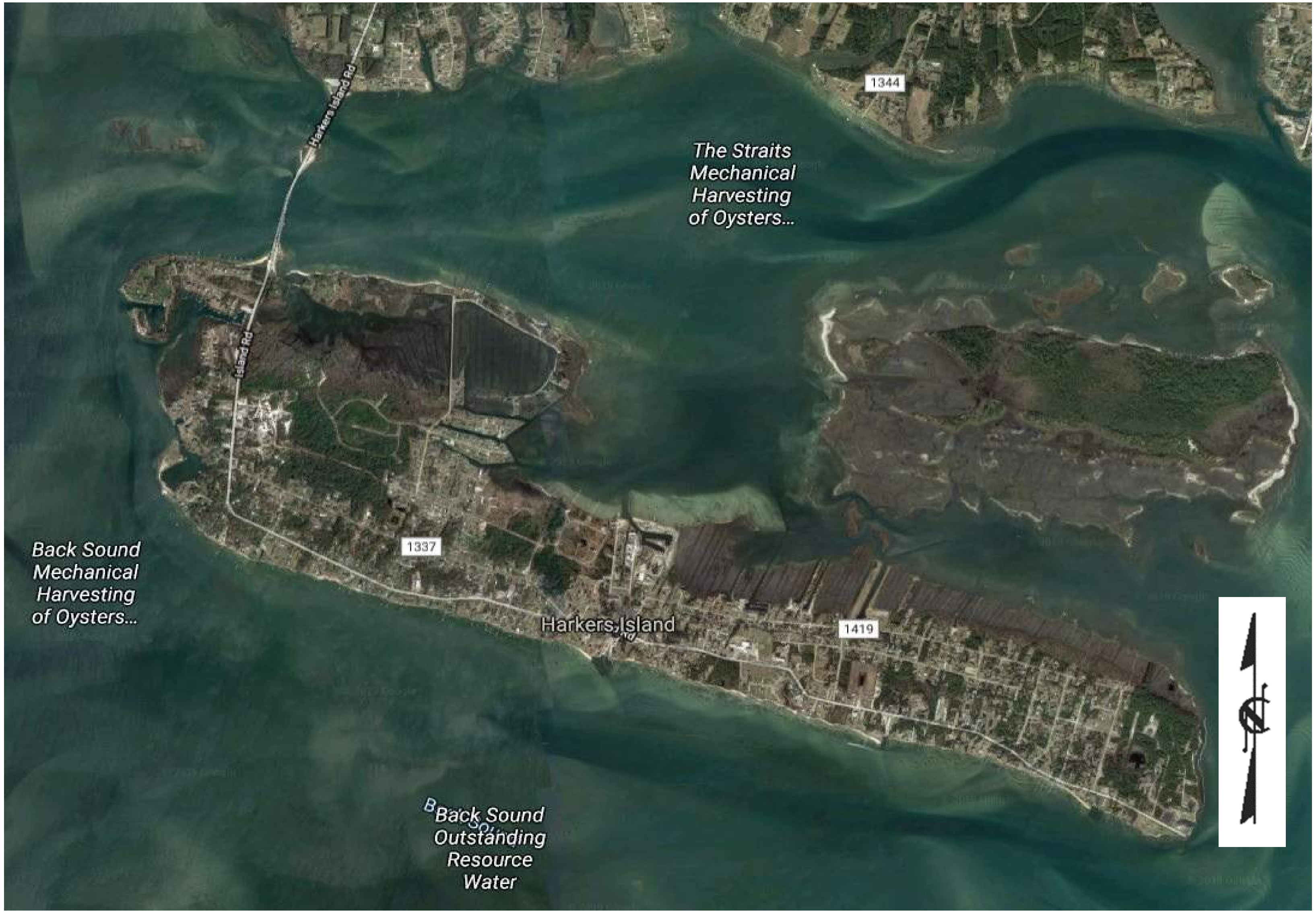
Otway
Cape Lookout National Seashore
Morehead City
Atlantic Beach
Harkers Island
Onslow Bay
Cape Lookout

Harkers Island, NC



Harkers Island, NC

Bridge No. 96

- Built 1970
- Superstructure Replacement 2013
- Functionally Obsolete




Bridge No. 96

- Built 1970
- Superstructure Replacement 2013
- Functionally Obsolete

Bridge No. 73

- Built 1969
- Posted SV 24, TTST 37
- Structurally Deficient

Leadup to Harkers Island

- 2005 – Glass Fiber Reinforced Polymer (GFRP) Bridge Deck
- 2014 – NCSU Research Project 2014-09: *CFRP Strands in Prestressed Cored Slab Units*
- 2017 – Transportation Pooled Fund Research Project – 5(363): *Evaluation of 0.7 inch Carbon Fiber Reinforced Polymer Pretensioning Strands in Prestressed Beams*

Significance of the Harkers Island Bridge Replacement Project

Project Utilizing Innovative Technology:

- Carbon Fiber Reinforced Polymer (CFRP) Strands
- Glass Fiber Reinforced Polymer (GFRP) Bars

Significance of the Harkers Island Bridge Replacement Project

Advantages of FRP Strands & Bars:

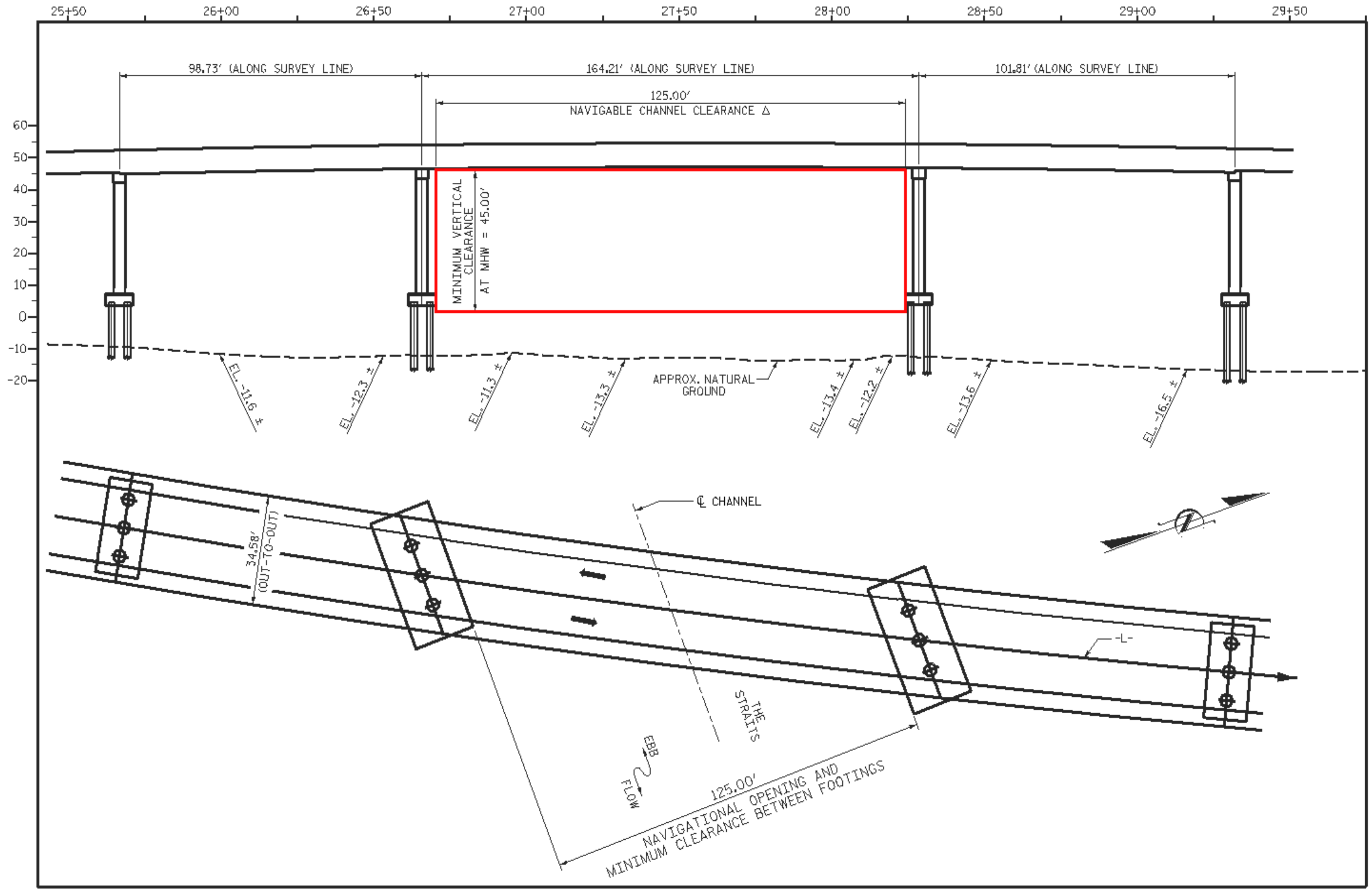
- Superior Corrosion Resistance
- High Tensile Strength
- Lightweight


Bridge No. 73
Bridge No. 96

Proposed Structure: 3,200’-0”
28 Spans

Navigational Channel

- 45' Min. Vertical Clearance
- 125' Min. Horizontal Clearance
- Vessel Impact



Harkers Island Bridge Project Details

- Cast-in-place Concrete (Superstructure* & Substructure)
  - Glass Fiber Reinforced Polymer (GFRP) Bars

Harkers Island Bridge Project Details

- Cast-in-place Concrete (Superstructure* & Substructure)
  - Glass Fiber Reinforced Polymer (GFRP) Bars

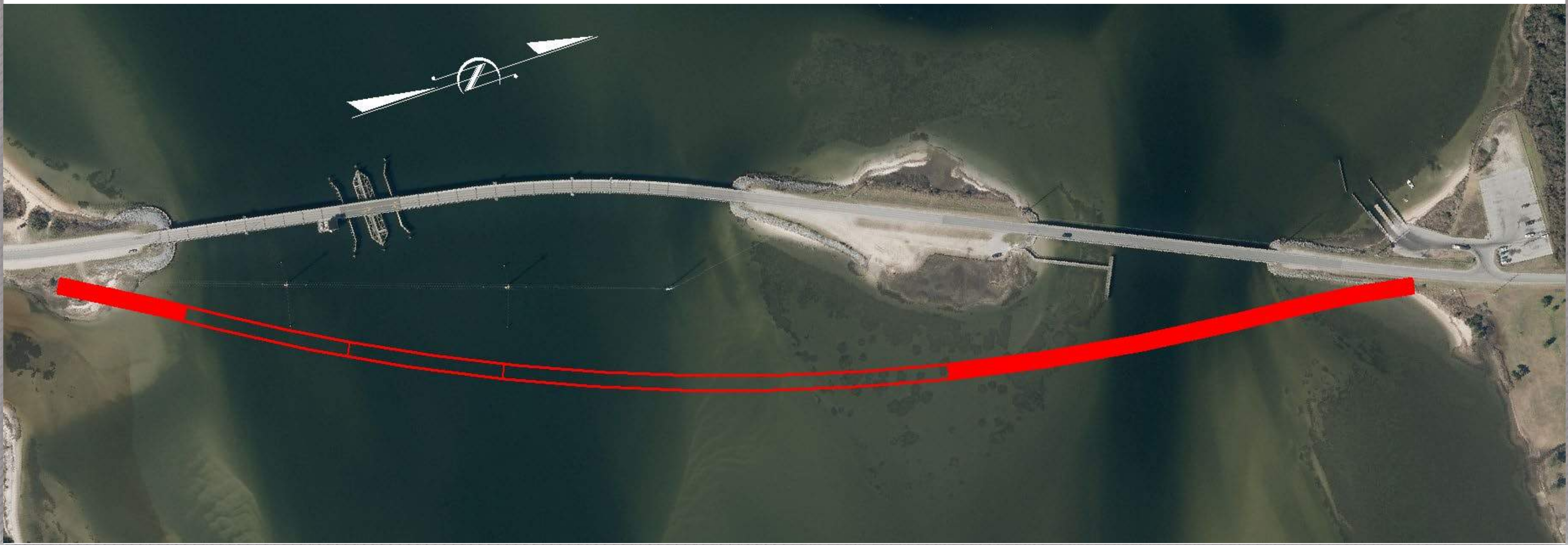
- Prestressed Concrete Girders
  - Carbon Fiber Reinforced Polymer (CFRP) Strands
  - GFRP Stirrup Option
  - CFRP Stirrup Option

Harkers Island Bridge Project Details

- Cast-in-place Concrete (Superstructure* & Substructure)
    - Glass Fiber Reinforced Polymer (GFRP) Bars
- Prestressed Concrete Girders
    - Carbon Fiber Reinforced Polymer (CFRP) Strands
    - GFRP Stirrup Option
    - CFRP Stirrup Option
- Prestressed Concrete Piles
    - CFRP Strands
    - CFRP Spiral

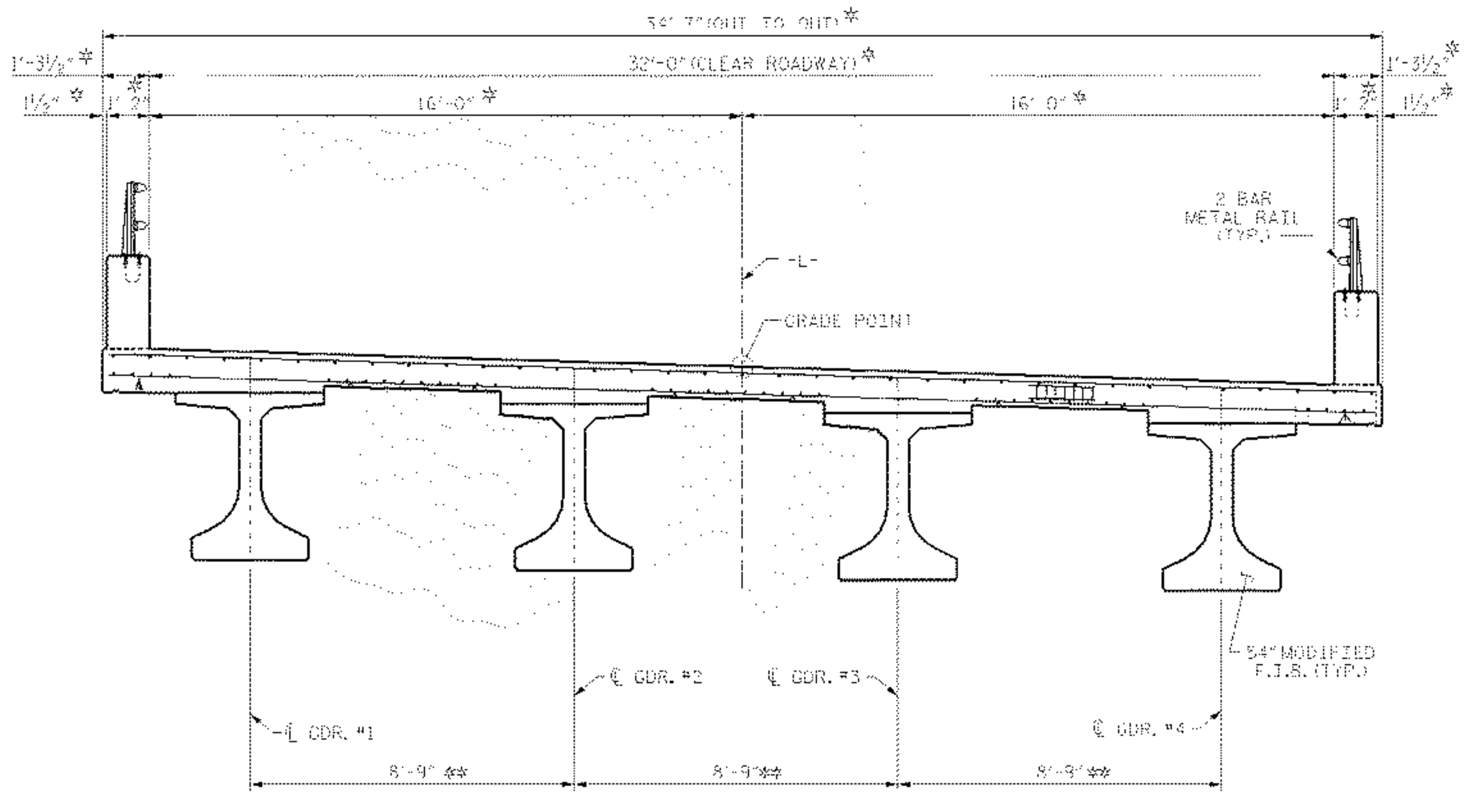
54” F.I.B. Prestressed Concrete Girder

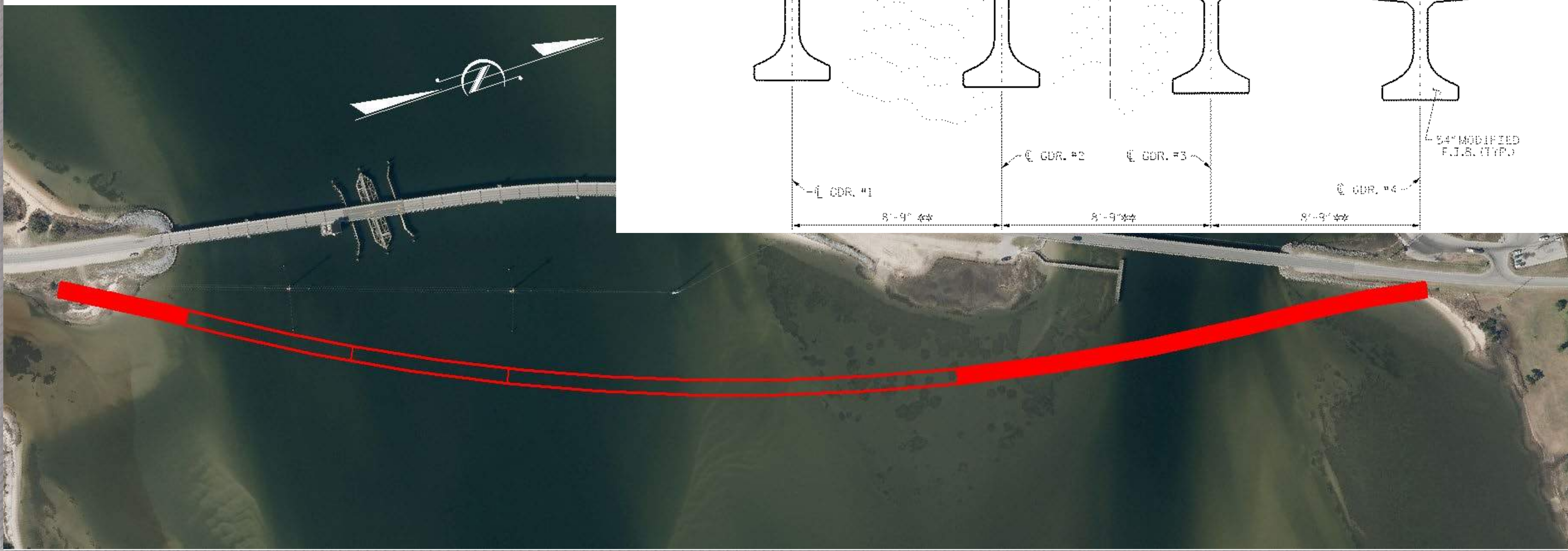
- 14 Spans
- Total # of Girders: 56
- Approximate Span Length: 100’



54" F.I.B. Prestressed Concrete Girder

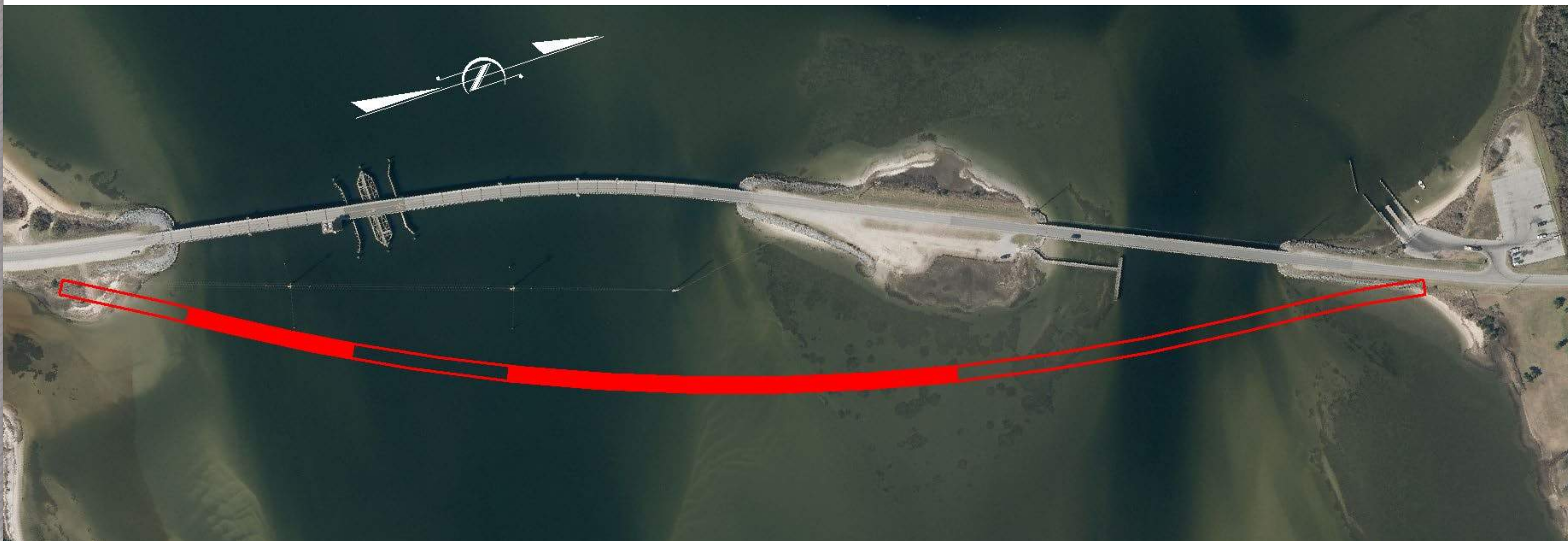
- 14 Spans
- Total # of Girders: 56
- Approximate Span Length: 100'
- Girder Spacing: 8'-9"





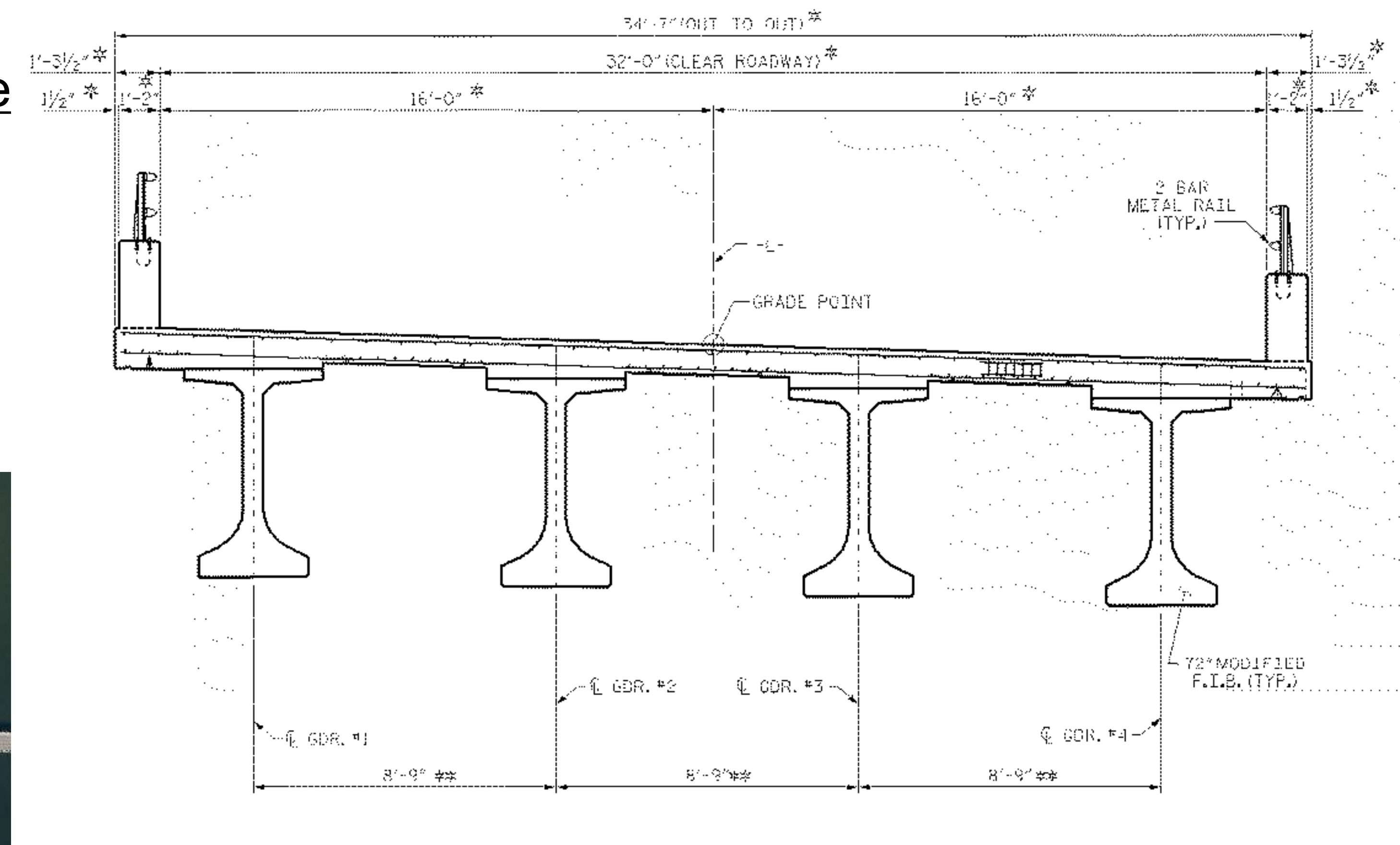
72” F.I.B. Prestressed Concrete Girder

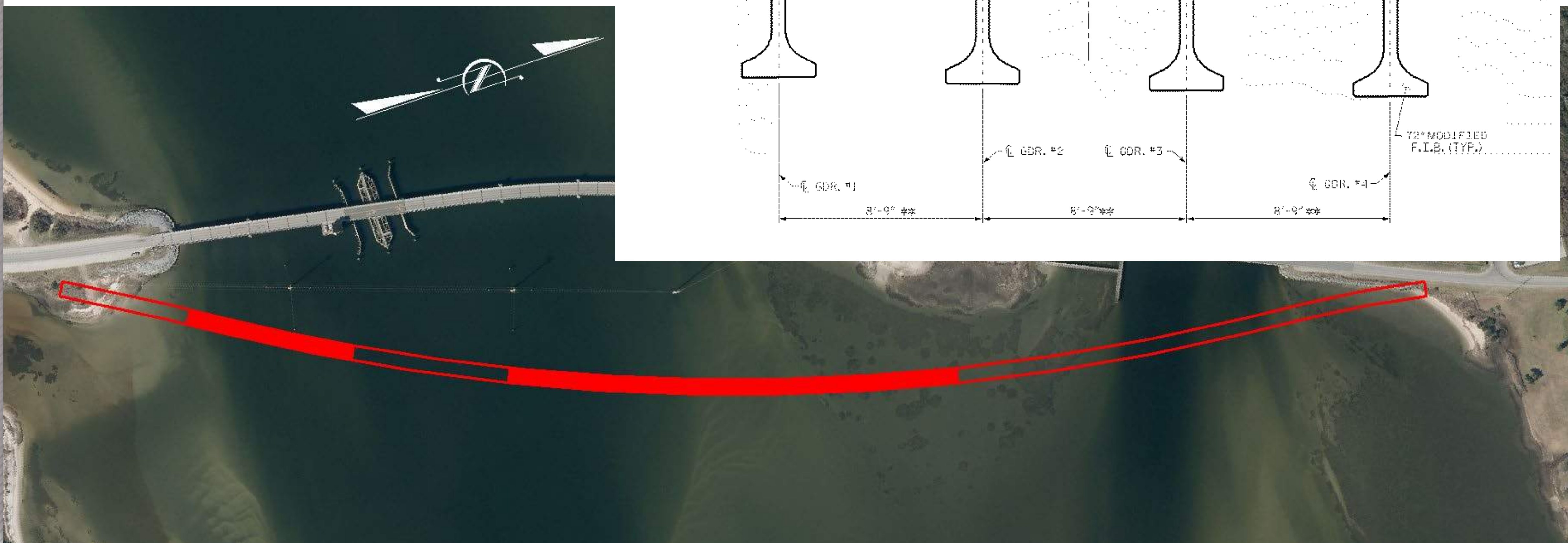
- 11 Spans
- Total # of Girders: 44
- Approximate Span Length: 130’



72” F.I.B. Prestressed Concrete Girde

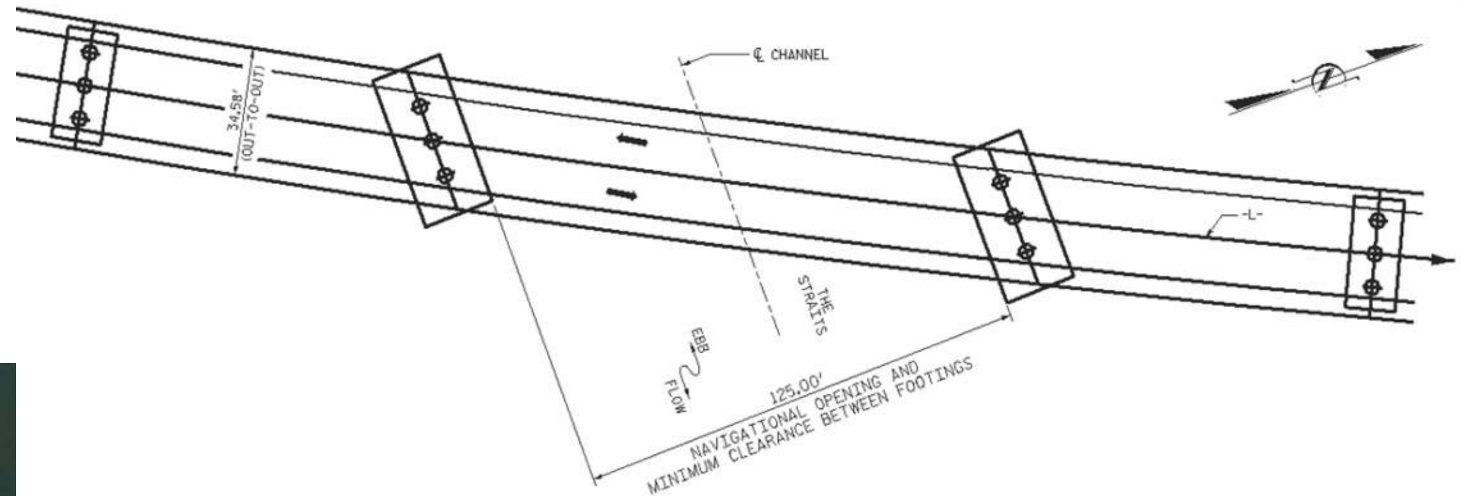
- 11 Spans
- Total # of Girders: 44
- Approximate Span Length: 130’
- Girder Spacing: 8’-9”





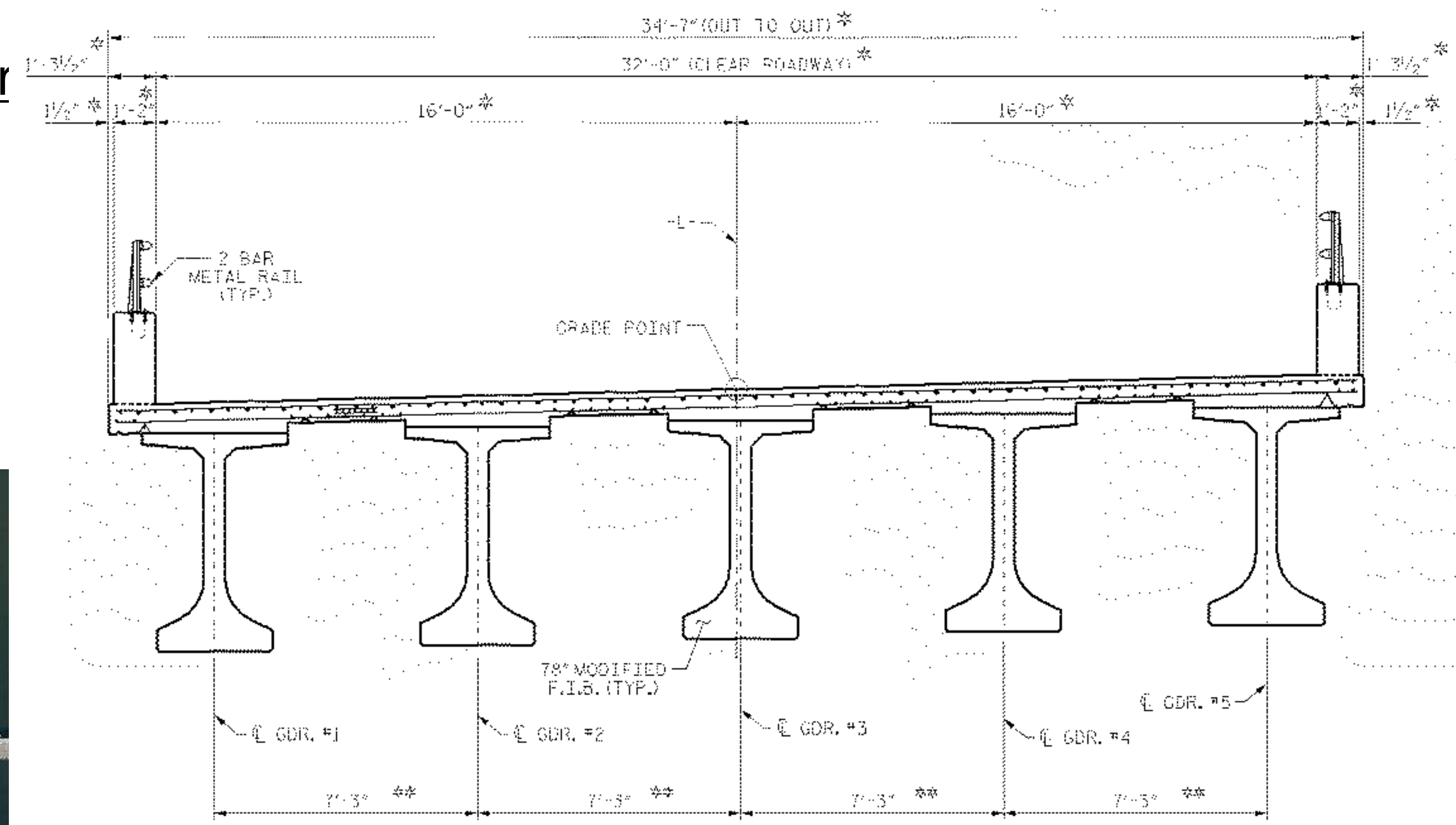
<u>78” F.I.B. Prestressed Concrete Girder</u>

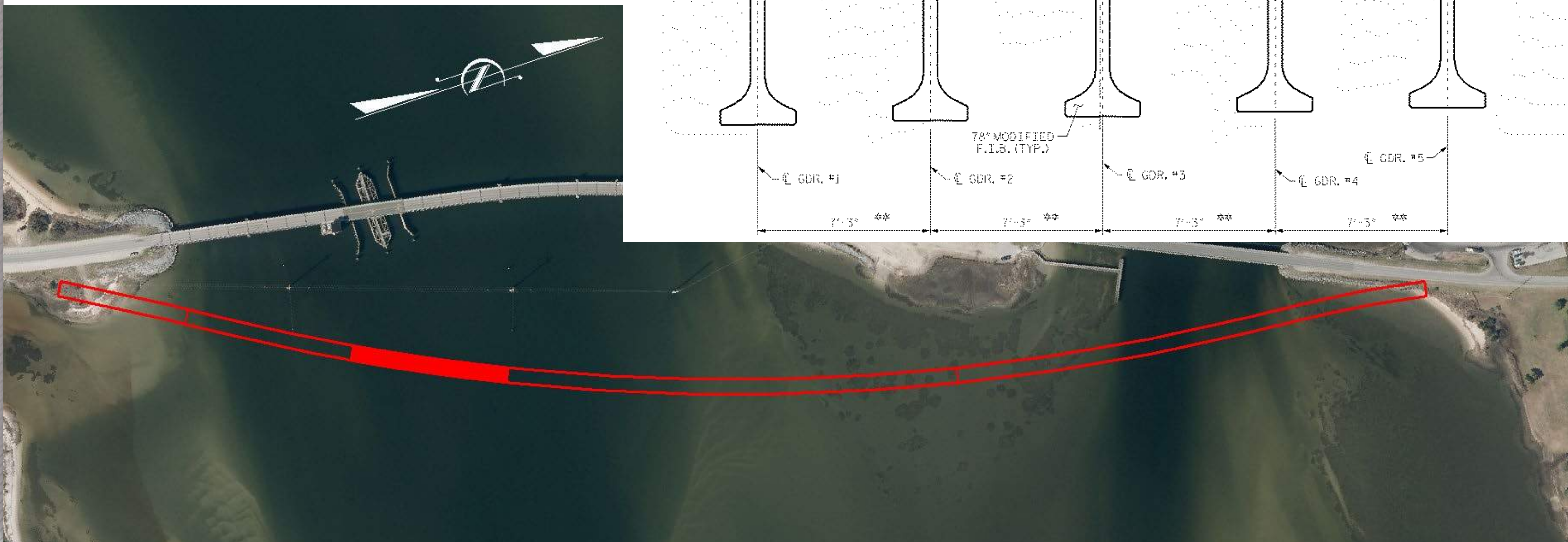
- 3 Spans
- Total # of Girders: 15
- Channel Span Length: 164’



78” F.I.B. Prestressed Concrete Girder

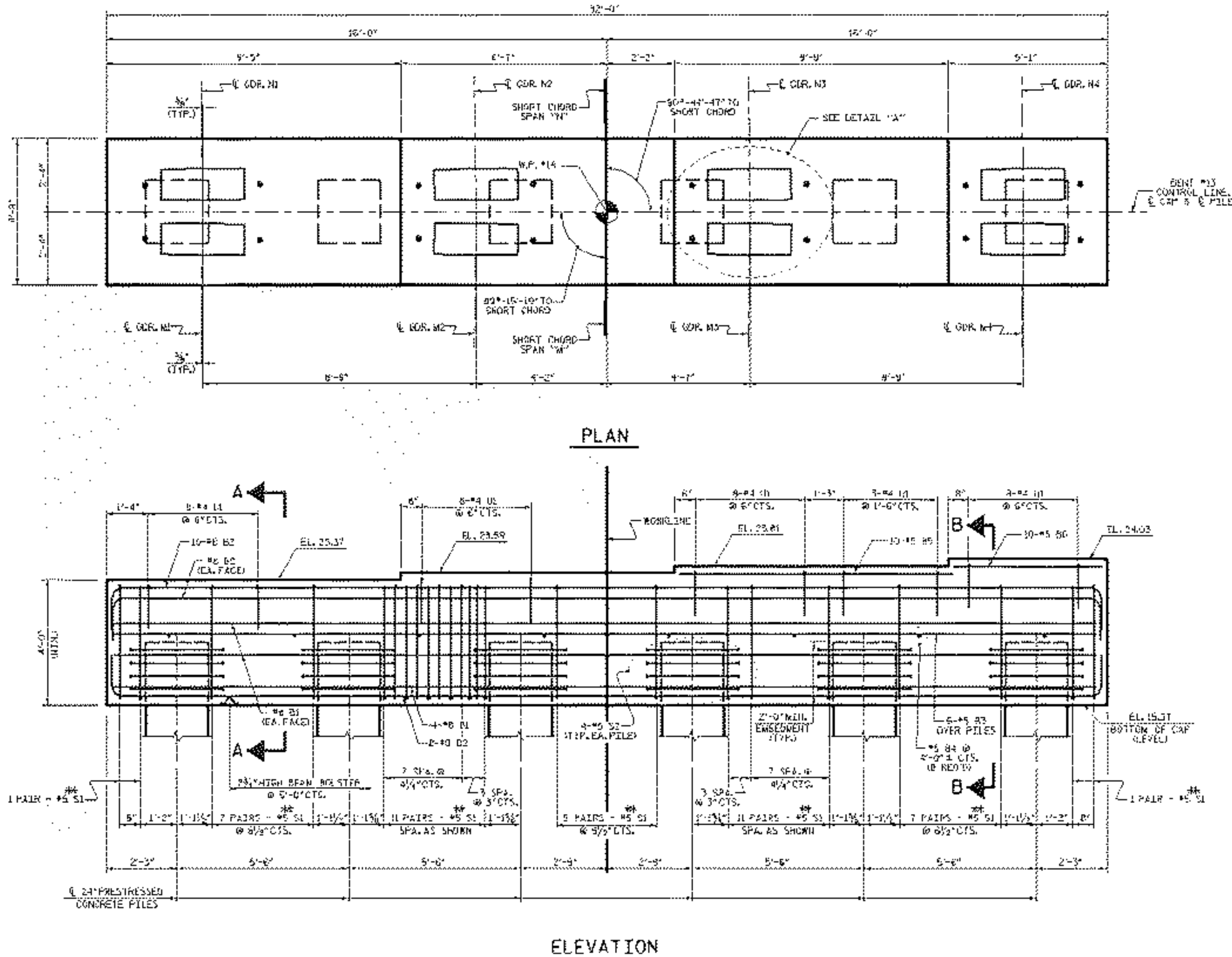
- 3 Spans
- Total # of Girders: 15
- Channel Span Length: 164’
- Girder Spacing: 7’-3”





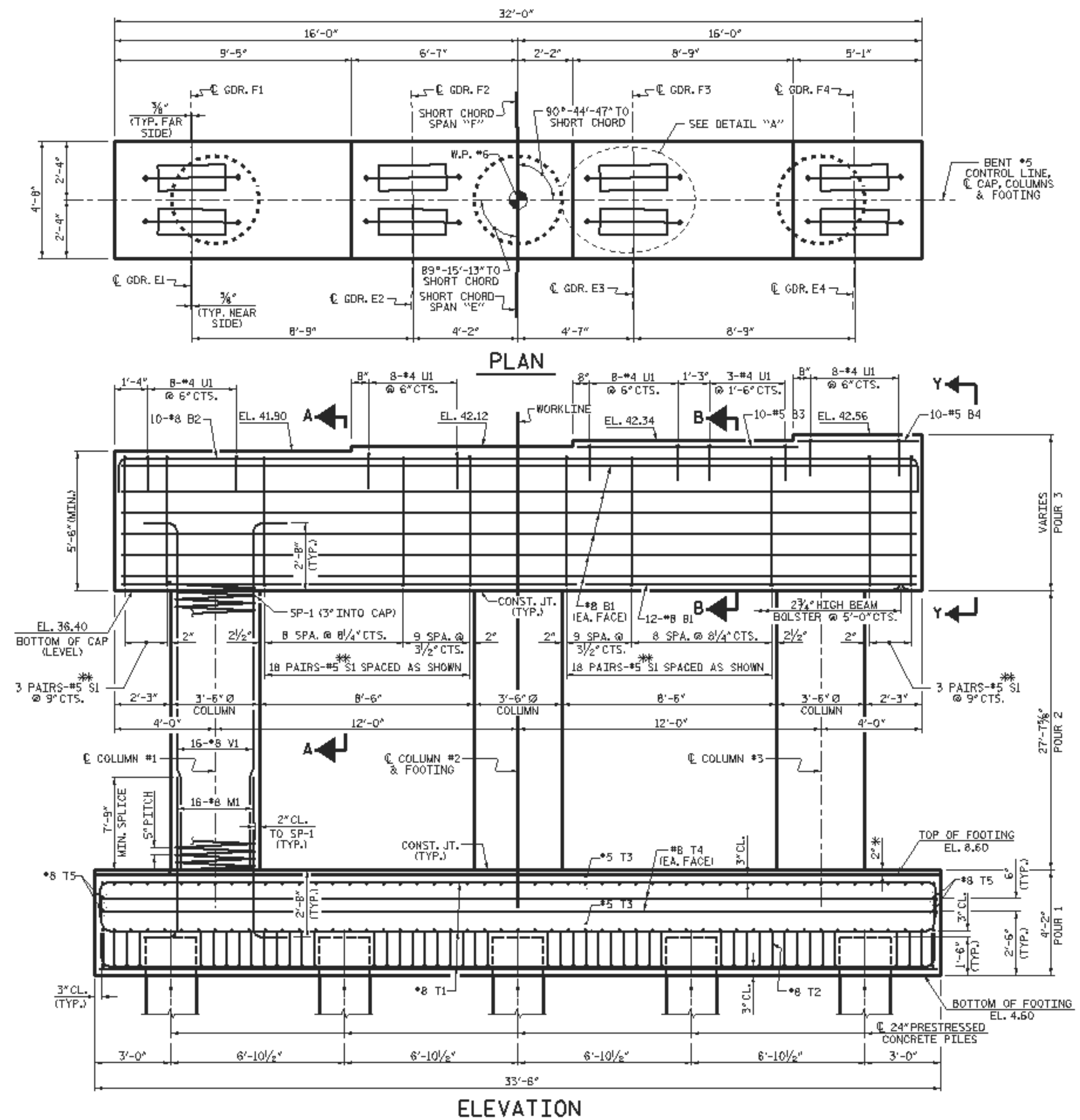
Pile Bents

- 24” Prestressed Concrete Piles
- 6 & 5 Pile Arrangement



Pile Bents
- 24” Prestressed Concrete Piles
- 6 & 5 Pile Arrangement

Approach Footing Bents
- 3’-6” Dia. Columns
- 10 – 24” Prestressed Concrete Piles



Pile Bents

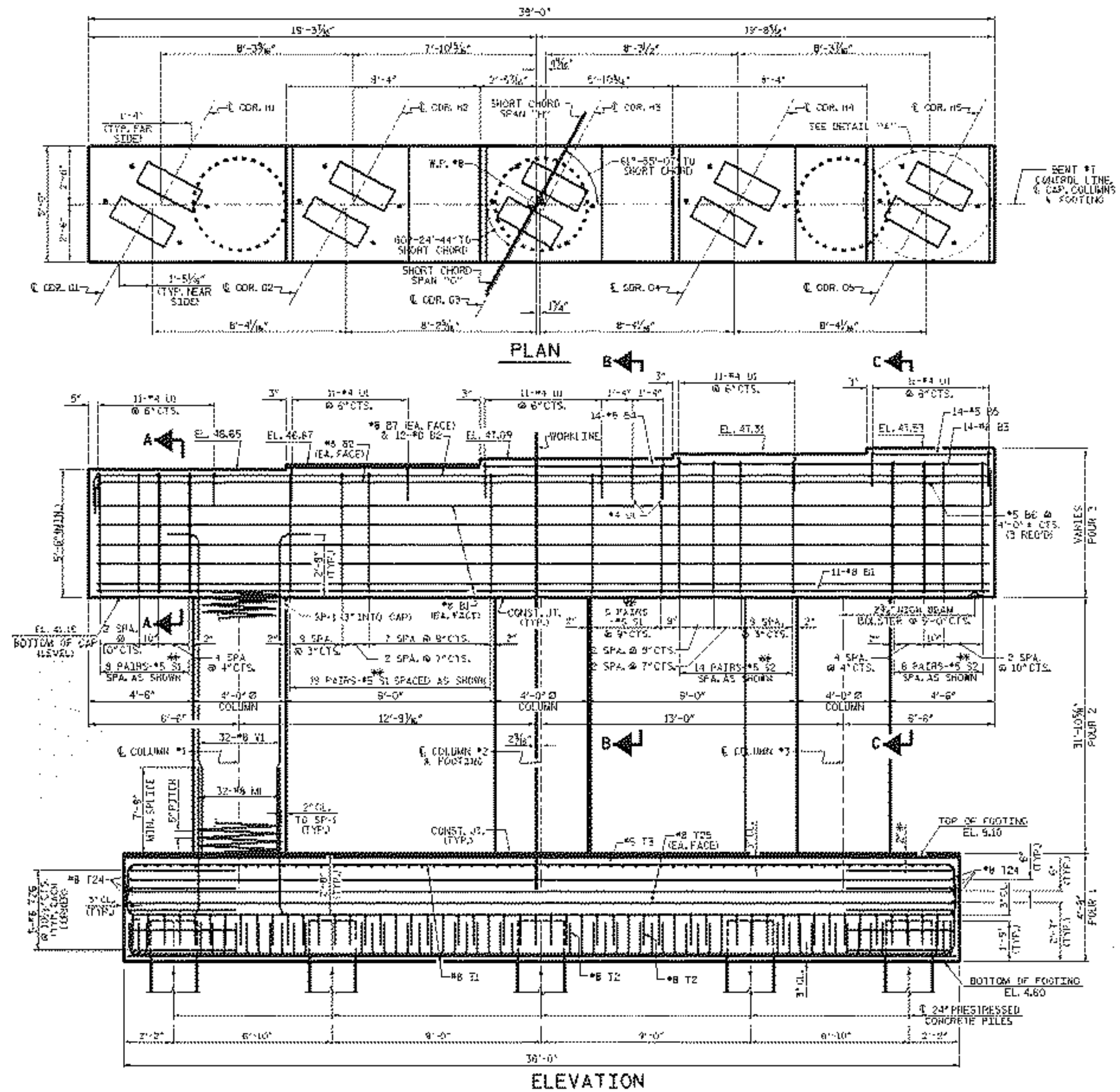
- 24” Prestressed Concrete Piles
- 6 & 5 Pile Arrangement

Approach Footing Bents

- 3’-6” Dia. Columns
- 10 – 24” Prestressed Concrete Piles

Channel Footing Bents

- 4’-0” Dia. Columns
- 15 – 24” Prestressed Concrete Piles



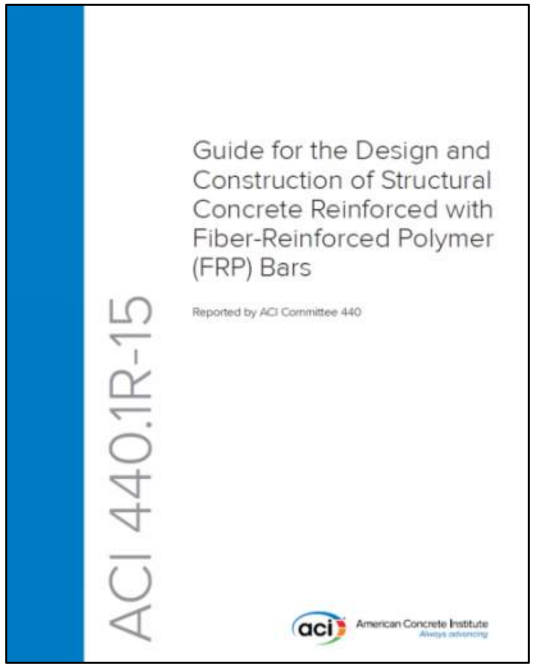
Design Challenges

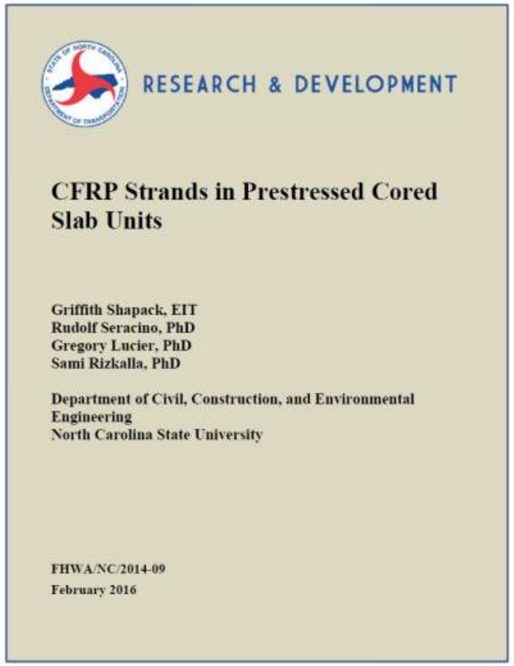
1. Design Codes, Manuals, & References

2. Material Considerations
   - Design
   - Detailing

Codes, Manuals, & References:

1. ACI 440.1 *Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars*
2. NCDOT/NC State Research Project 2014-09 *CFRP Strands in Prestressed Cored Slab Units*





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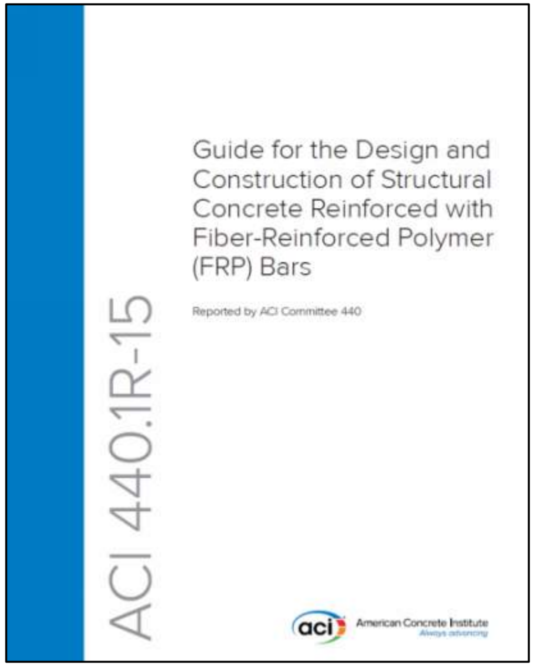
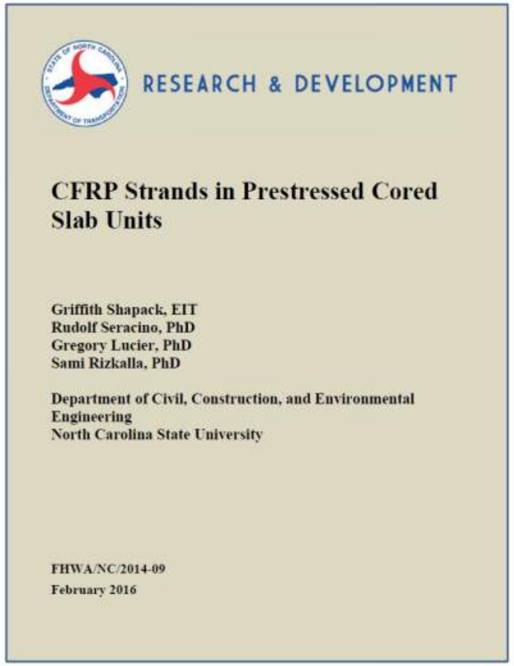

ACI 440.1R-15

Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars

Reported by ACI Committee 440

aci American Concrete Institute
Always advancing


RESEARCH & DEVELOPMENT

CFRP Strands in Prestressed Cored Slab Units

Griffith Shapack, EIT
Rudolf Seracino, PhD
Gregory Lucier, PhD
Sami Rizkalla, PhD

Department of Civil, Construction, and Environmental Engineering
North Carolina State University

FHWA/NC/2014-09
February 2016

MDOT Michigan Department of Transportation

FDOT

VDOT Virginia Department of Transportation

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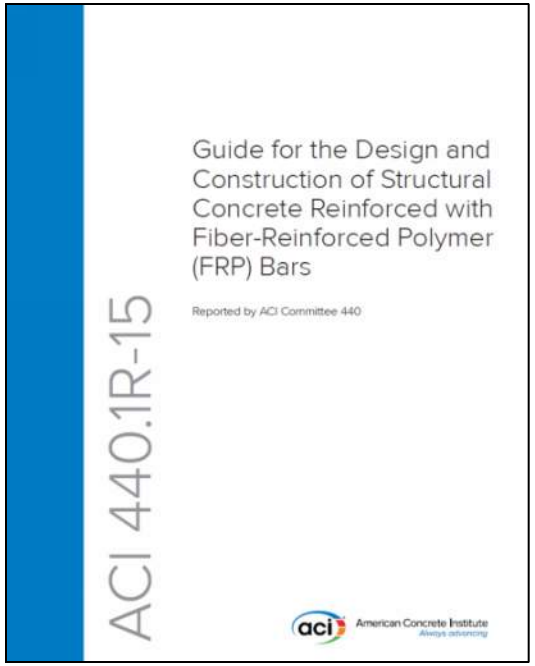
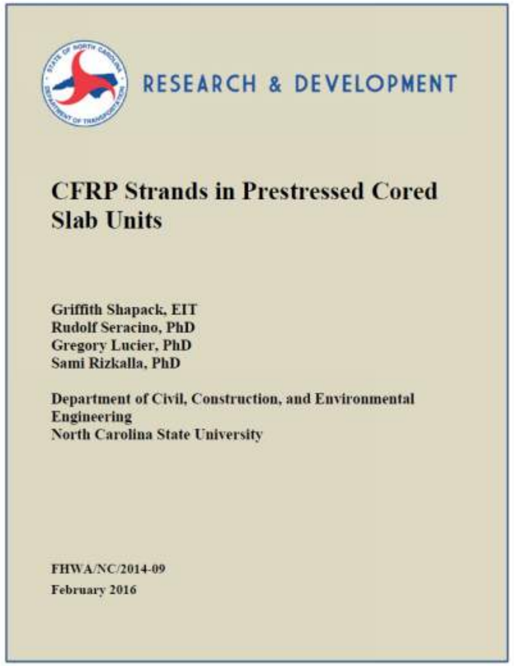
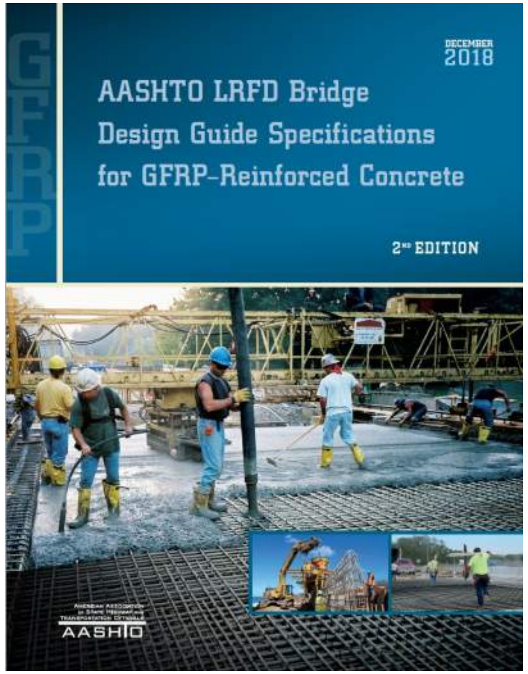
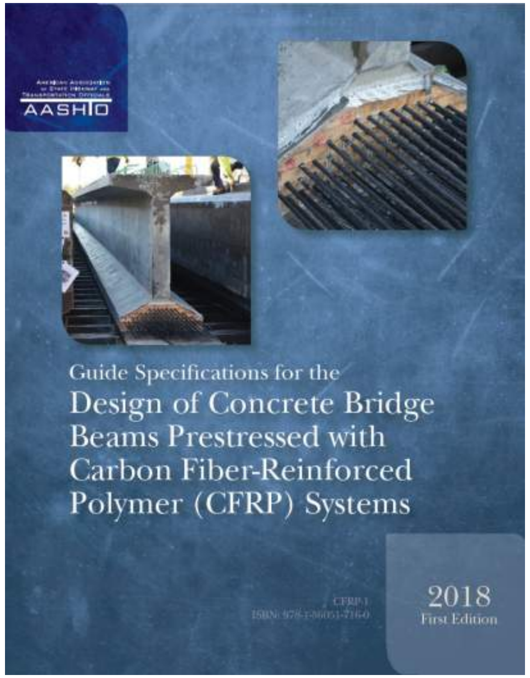
2. NCDOT/NC State Research Project 2014-09 *CFRP Strands in Prestressed Cored Slab Units*
3. *Michigan, Florida, & Virginia DOT*
4. AASHTO LRFD *Bridge Design Specification for GFRP-Reinforced Concrete, 2nd Edition*
5. AASHTO *Guide Specification for the Design of Concrete Bridge Beams Prestressed with CFRP Systems*









MDOT Michigan Department of Transportation

FDOT

VDOT Virginia Department of Transportation

Material Considerations

- Direct Substitution between FRP and Steel Strand/Reinforcement is not possible

- Modulus of Elasticity

Material Considerations

CFRP Strands vs. Steel Strands

	Steel Strands	CFRP Strands
Diameter (in.)	0.6	0.6
Cross Section Area (in^2)	0.217	0.179
Ultimate/Guaranteed Strength (ksi)	$f_u = 270$	$f_{gu} = 339$
Yield Strength (ksi)	$f_y = 243$	$f_y = N/A$
Elastic Modulus (ksi)	$E_p = 28{,}500$	$E_p = 21{,}900$
Allowable Prestressing Stress immediately prior to Transfer (f_{pbt})	AASHTO LRFD $f_{pbt} \leq 0.75 f_{pu}$	AASHTO CFRP $f_{pbt} \leq 0.70 f_{pgu}$
Allowable (f_{pbt})	202.5 (44 kip/strand)	237.3 (42.5 kip/strand)

Material Considerations

CFRP Strands vs. Steel Strands

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Diameter (in.)	0.6	0.6
Cross Section Area (in^2)	0.217	0.179
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Allowable (f_{pbt})	202.5 (44 kip/strand)	237.3 (42.5 kip/strand)

1:1

Material Considerations

GFRP Reinforcement vs. Steel Reinforcement

GFRP Physical & Mechanical Properties						
Bar Size Designation	Nominal Diameter (in.)	Nominal Cross Section Area (in^2)	Guaranteed Tensile Strength (ksi)	Yield Strength (ksi)	Elastic Modulus (ksi)	Unit Weight/Length (lbs/ft)
4	0.500	0.20	110	N/A	6,700	0.189
5	0.625	0.31	105	N/A	6,700	0.287
6	0.750	0.44	100	N/A	6,700	0.408
7	0.875	0.60	95	N/A	6,700	0.544
8	1.000	0.79	90	N/A	6,700	0.730

Steel Physical & Mechanical Properties						
Bar Size Designation	Nominal Diameter (in.)	Nominal Cross Section Area (in^2)	Tensile Strength (ksi)	Yield Strength (ksi)	Elastic Modulus (ksi)	Unit Weight/Length (lbs/ft)
4	0.500	0.20	90	60	29,000	0.668
5	0.625	0.31	90	60	29,000	1.043
6	0.750	0.44	90	60	29,000	1.502
7	0.875	0.60	90	60	29,000	2.044
8	1.000	0.79	90	60	29,000	2.670

Material Considerations

GFRP Reinforcement vs. Steel Reinforcement

GFRP Physical & Mechanical Properties						
Bar Size Designation	Nominal Diameter (in.)	Nominal Cross Section Area (in^2)	Guaranteed Tensile Strength (ksi)	Yield Strength (ksi)	Elastic Modulus (ksi)	Unit Weight/Length (lbs/ft)
4	0.500	0.20	110	N/A	6,700	0.189
5	0.625	0.31	105	N/A	6,700	0.287
6	0.750	0.44	100	N/A	6,700	0.408
7	0.875	0.60	95	N/A	6,700	0.544
8	1.000	0.79	90	N/A	6,700	0.730

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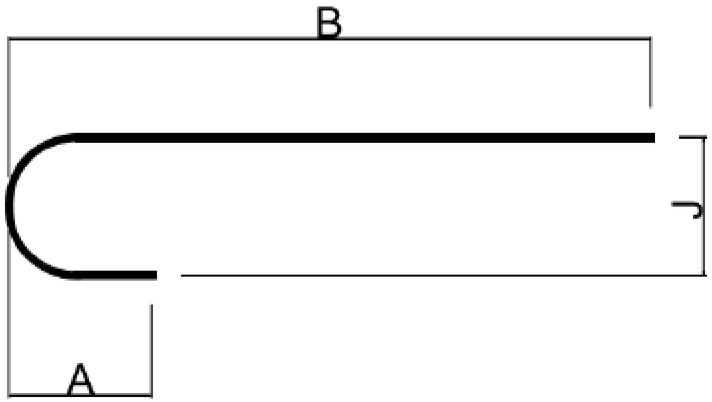
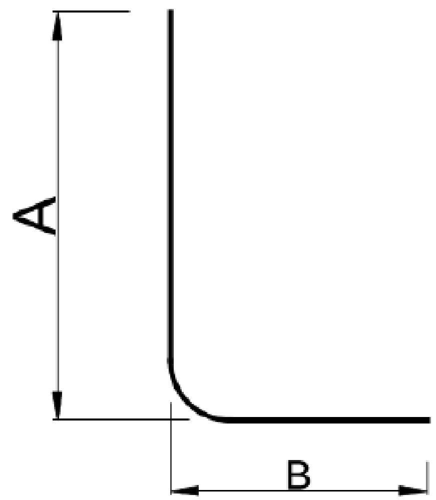
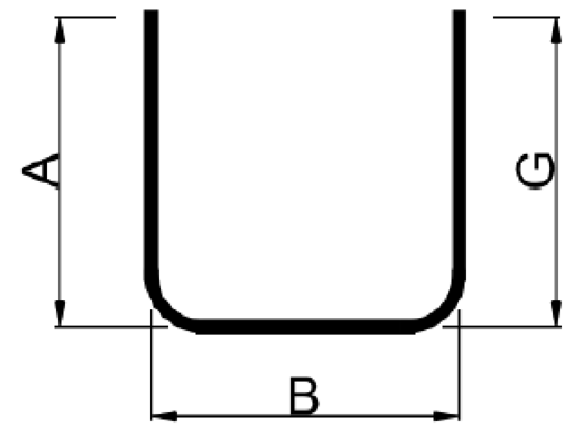
Material Considerations

Bar Detailing:







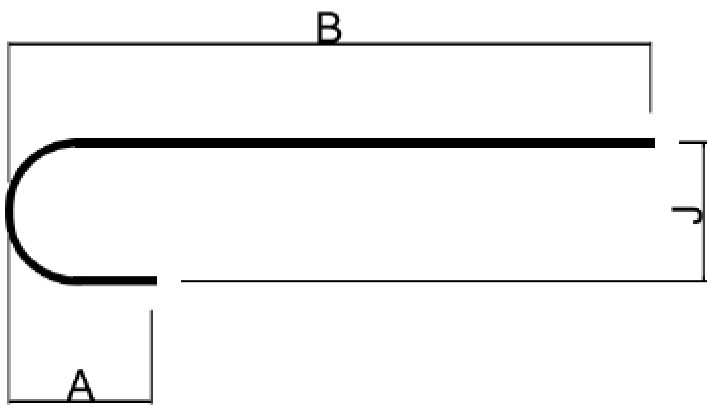
		A & B	J
#	DIA (in)	MAX	(in)
#2	1/4	8’–3”	3½
#3	3/8	8’–3”	3¾
#4	1/2	8’–3”	5
#5	5/8	8’–3”	6¼
#6	3/4	8’–3”	7½
#7	7/8	8’–3”	9¾
#8	1	8’–3”	10

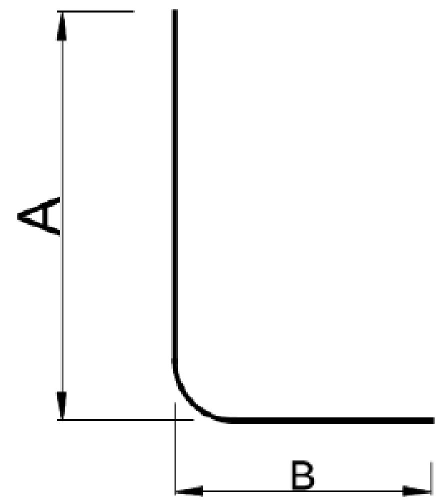
		A	B
#	DIA (in)	MAX	MAX
#2	1/4	6’	5’-8”
#3	3/8	6’	5’-8”
#4	1/2	6’-3”	5’-10”
#5	5/8	6’-4”	5’-11”
#6	3/4	6’-5”	6’
#7	7/8	6’-8”	6’-3”
#8	1	6’-8”	6’-3”

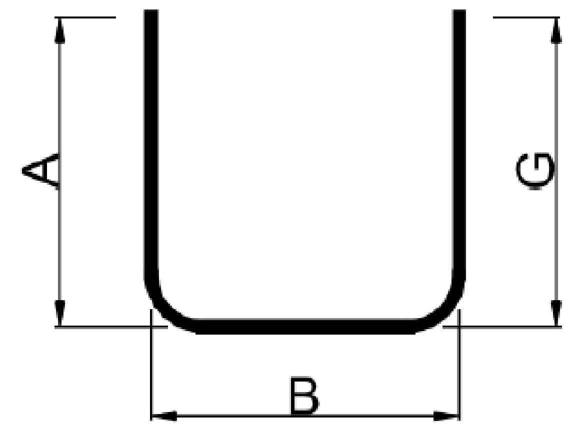
		A & G	B	
#	DIA (in)	MAX	MIN	MAX
#2	1/4	5’-8”	9”	6’
#3	3/8	5’-8”	9”	6’
#4	1/2	5’-10”	11”	6’-3”
#5	5/8	5’-11”	1’	6’-4”
#6	3/4	6’	1'	6’-5”
#7	7/8	6’-3”	1’-4”	6’-8”
#8	1	6’-3”	1’-4”	6’-8”

Material Considerations

Bar Detailing:







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		A	B
#	DIA (in)	MAX	MAX
#2	1/4	6'	5'-8"
#3	3/8	6'	5'-8"
#4	1/2	6'-3"	5'-10"
#5	5/8	6'-4"	5'-11"
#6	3/4	6'-5"	6'
#7	7/8	6'-8"	6'-3"
#8	1	6'-8"	6'-3"

		A & G	B	
#	DIA (in)	MAX	MIN	MAX
#2	1/4	5'-8"	9"	6'
#3	3/8	5'-8"	9"	6'
#4	1/2	5'-10"	11"	6'-3"
#5	5/8	5'-11"	1'	6'-4"
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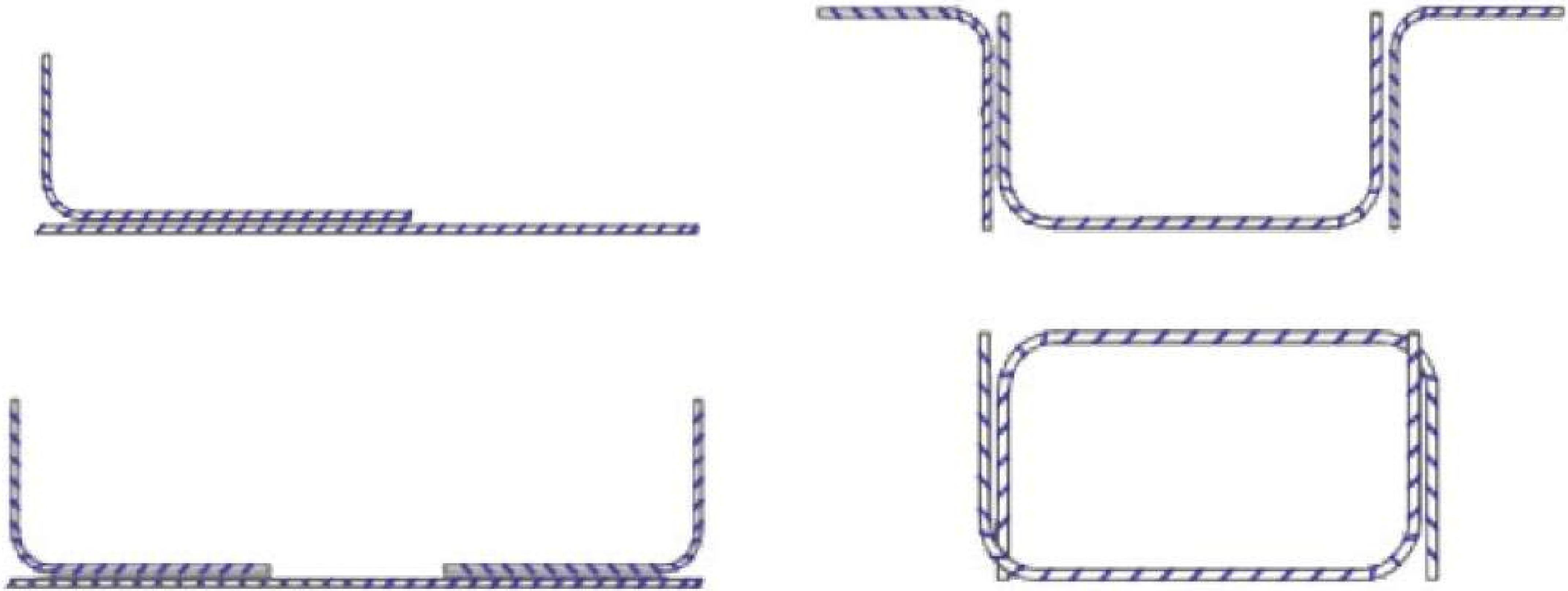
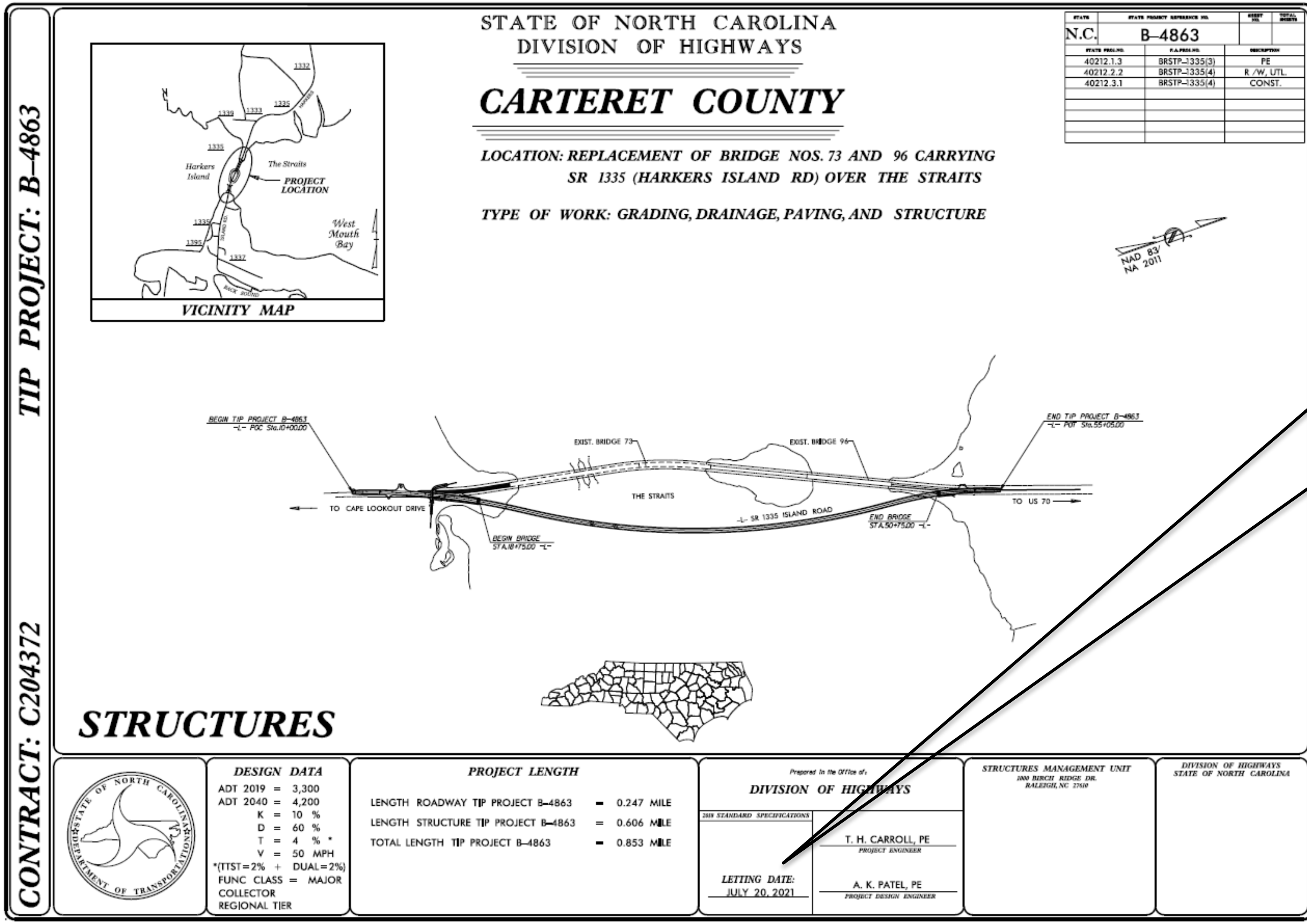
#7	7/8	6'-3"	1'-4"	6'-8"
#8	1	6'-3"	1'-4"	6'-8"

Material Considerations

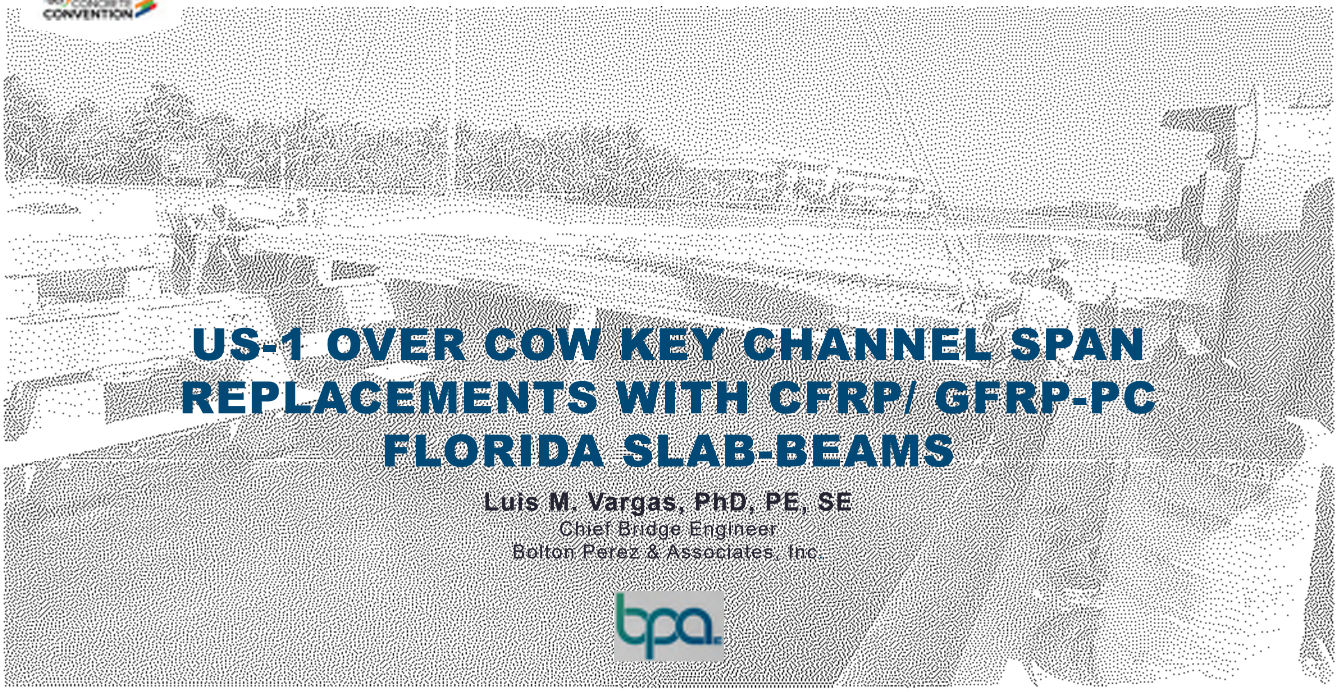
Bar Detailing:





LETTING DATE:
JULY 20, 2021

Stay Tuned!



US-1 OVER COW KEY CHANNEL SPAN REPLACEMENTS WITH CFRP/ GFRP-PC FLORIDA SLAB-BEAMS

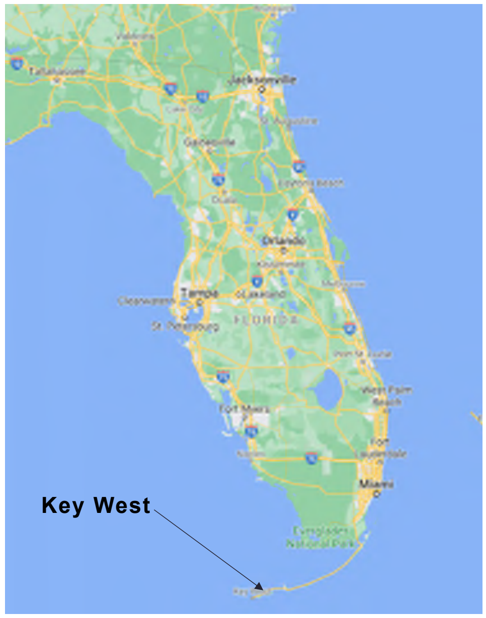
Luis M. Vargas, PhD, PE, SE
Chief Bridge Engineer
Bolton Perez & Associates, Inc.

Outline

- Project Overview
- Deterioration of Superstructure
- Replacement Alternatives
- Project Design
- Construction Activities

Project Overview

Project Location



- US-1 over Cow Key Channel Bridges located in Florida Keys
- There are 43 Islands connected by bridges

Project Overview

Project Location

US-1 / SR-5 over Cow Key Channel

- US-1 over Cow Key Channel Bridges (NB-900086 & SB-900125) located in Florida Keys
- Bridge within the Florida Keys National Marine Sanctuary
- Evacuation route during Hurricane season
- Bridge type: Nine-span Sonovoid superstructure on pile bents, built between 1978 & 1985
- Aggressive Environment

US-1 Over Cow Key Channel Span Replacements with CFRP/GFRP-PC Florida Slab-Beams

Project Overview
Scope Elements

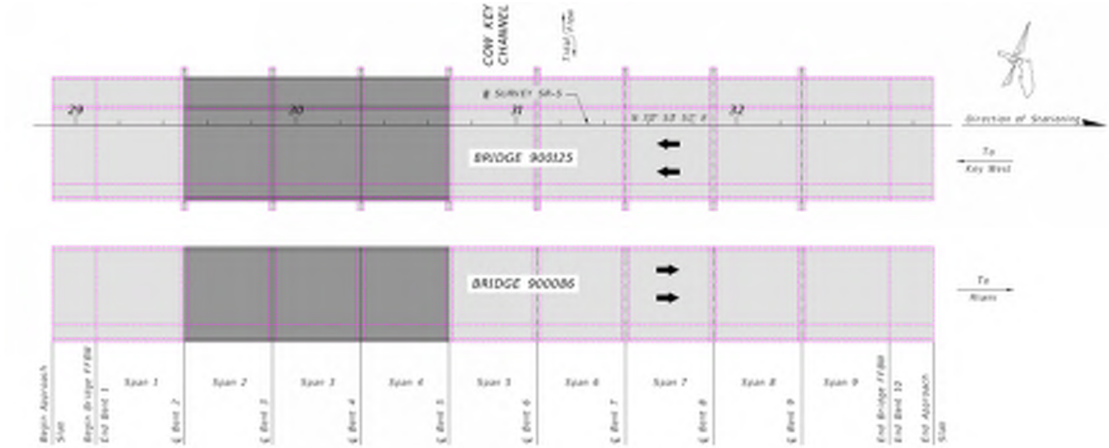
Scope Elements
- Project Management
- Structures
- Load rating evaluation
- Roadway
- S&PM
- Temporary signalization
- Traffic Analysis
- Survey
- Utility coordination
- Public Involvement
- Post design services

Project Overview
Project Team

Project Team
- Bolton Perez & Associates
- Florida Department of Transportation – District 6
  - Bridge Maintenance
  - Central Office
- City of Key West
- Monroe County
- WSP – Construction Engineers and Inspection
- Construction
  - Kiewit Infrastructure
  - Gate Precast Company (T. Newton)
    - Forms: Hamilton Form Companies
    - GFRP Rebar: Pultrall (VROD)
    - CFRP Rebar: Tokyo Rope Mfg. Co.

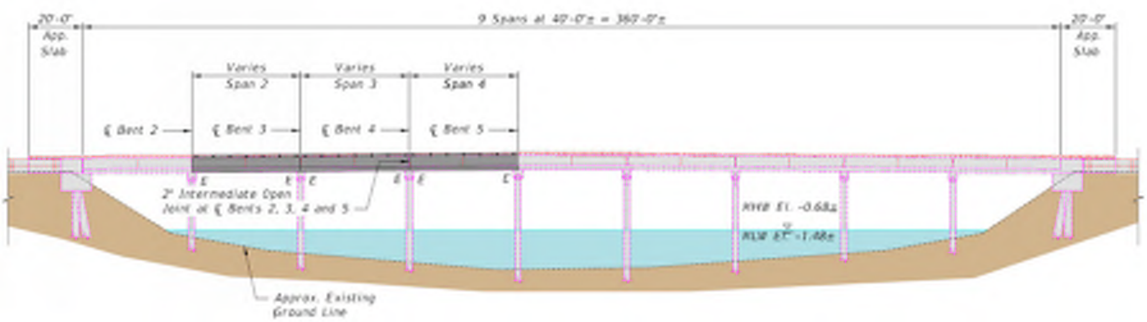
Project Overview

Bridge Plan



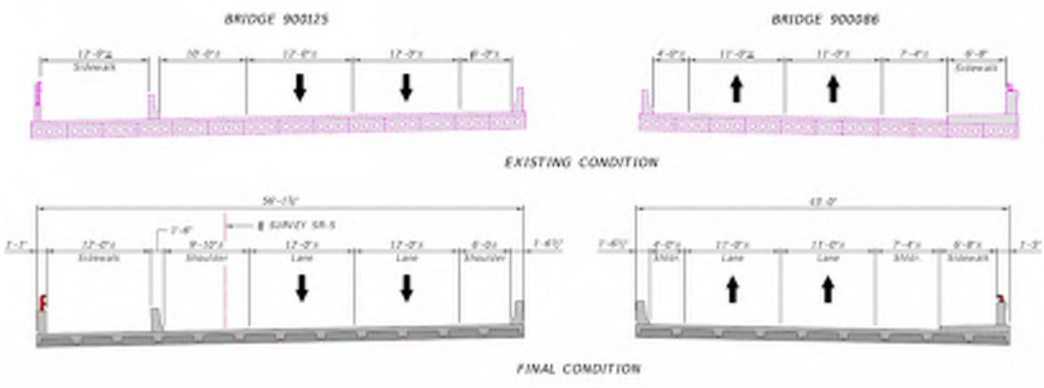
Project Overview

Bridge Elevation



Project Overview

Typical Section



Existing section:
- 18" Sonovoid + 5" deck
- Overall depth 23"

Proposed section:
- 12" FSB + 6" deck
- Overall depth 18"
- Lighter superstructure

Deterioration of Superstructure

Deterioration

- Panels within splash zone exposed to stream of water from motorized recreational water-vehicles
- Underside of Sonovoid panels in Spans 3 and 4 experienced severe damage due reinforcing steel corrosion
- Deck underside in poor condition with evident concrete spalling and exposed reinforcing
- Load rating factors dropped to 0.68 & 1.25; temporary remediation was implemented by underpinning some panels
- Inspection report of May 2017 & Corrosion report from State Materials Office (SMO) determined the replacement of Spans 3 & 4 of NB & SB bridges
- FDOT SMO produced a second report showing corrosion initiation on Span 2, this span was added to scope

Deterioration of Superstructure

Exposed reinforcing, spalling, cracking & delamination

Underpinning at midspan

Replacement Alternatives

Superstructure Alternatives

- Cast-in-Place (CIP Reinforced Concrete Slab) – rather robust in corrosive environments as the large amount of reinforcing offers ample redundancy
- CIP slabs require extensive false work, significant increase of load on substructure, increase in construction time
- Florida Slab Beam (FSB) – precast prestress panels -- First use on State Road
- Coordinated with CO (Steve Nolan), SMO (Ivan Lasa) and District (Pablo Orozco)
- Use of Innovative Materials: GFRP rebar and CFRP prestress
- First time use of GFRP & CFRP on FSB system, eliminating future corrosion issues
- Added protection penetrant sealer on the underside of the entire deck slab

Replacement Alternatives

Benefits of Propose Superstructure

Benefit of proposed Superstructure

- **FSB benefits**
  - FSB provides a lighter superstructure reducing demand on substructure
  - FSB allows accelerated construction since forms are not required to pour concrete deck
  - FSB are light members facilitating beam erection
- **GFRP & CFRP benefits**
  - Eliminates the need for additional concrete cover
  - Eliminates concrete additives
  - Eliminates waterproofing sealants for corrosion protection
  - Reduces labor and equipment costs
  - Longer service life
  - Reduces future maintenance costs

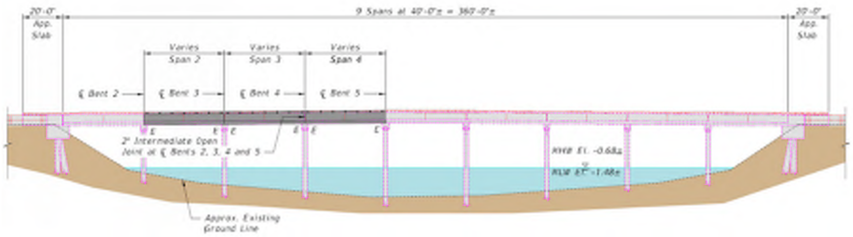
Project Design

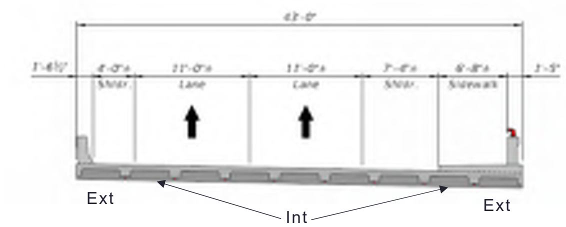
Criteria

Design Criteria

- AASHTO LRFD Bridge Design of Concrete Bridge Design Specifications, 8th Edition, 2017
- FDOT Structures Manual 2018
- AASHTO Guide Specification for the Design of Concrete Bridge Beams Prestresses with Carbon Fiber-Reinforced Polymer (CFRP) Systems, 1st Edition, 2018
- FDOT Standard Specifications for Road & Bridge Construction, 2019 – Sections 932 & 933
- No impact on existing foundation
- Environmental
  - Stringent turbidity requirements
  - Monitoring on construction activities

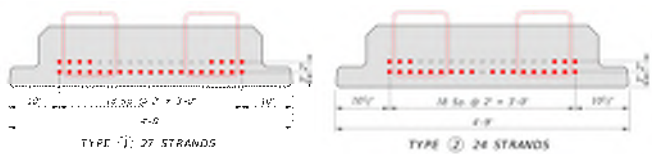
Project Design
FSB Design Br. 900086





FSB 12

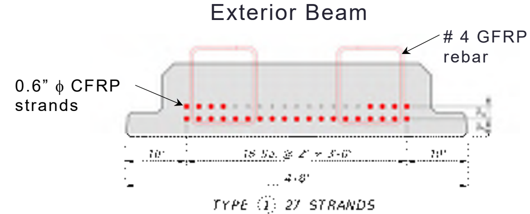
Exterior | Interior

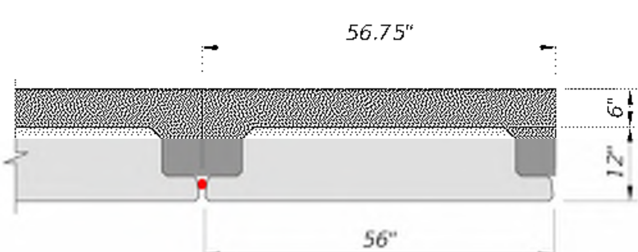


Project Design
FSB Design Br. 900086

Limit States
- Service
  - At release
  - Service I
    - Top flange of non-composite section
    - Top flange of composite section
  - Service III
    - Bottom flange
- Strength
  - Strength I

Exterior Beam

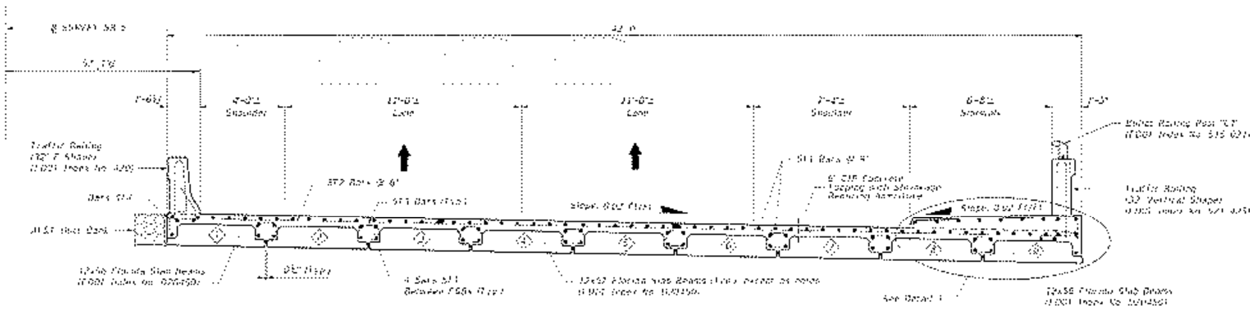




Project Design

FSB Design Br. 900086

Deck reinforcing



Project Design

FSB Design Br. 900086

Design Parameters

- Concrete
  - FSB f'_c = 8.5 ksi
  - Deck f'_c = 5.5 ksi
- GFRP: # 4 rebar
  - f_{fu} = 94 ksi
  - E_f = 6,500 ksi
- CFRP: 0.6” diameter 7 wire strands
  - $F_{pu\ CFRP}$ = 341 ksi
  - E_p = 22,400 ksi

Loads

- DC1: Non-composite loads
  - FSB 12x56
- DC2: Composite loads
  - Barriers = 0.091 klf/Bm
  - Sidewalk = 0.09 klf/Bm
- Composite loads (DW)
  - FWS = 0.056 klf/Bm
  - Utilities = 0.053 klf/Bm
- Design truck
  - HL 93
- Permit truck
  - FL 120

Project Design
FSB Design Br. 900086

Design truck controlling forces

Bending forces - Midspan
- M_{DC} = 229.0 k-ft
- M_{DW} = 18.8 k-ft
- M_{LL+IM} = 258.7 k-ft

Design forces - Midspan
- $M_{Serv\ I}$ = 503.1 k-ft
- $M_{Serv\ III}$ = 451.4 k-ft
- $M_{Str\ I}$ = 879.0 k-ft

Shear forces – At ends
- V_{DC} = 24.2 k
- V_{DW} = 1.94 k
- V_{LL+IM} = 54.7 k

Design forces – At ends
- $V_{Str\ I}$ = 130.3 k-ft

Project Design
FSB Design Br. 900086

Design results

Service I - Midspan
- Top Slab: $f_{c\text{-slab}}$ = 1.3 ksi < 0.6 $f'_{c\ Slab}$
- Top Flange: $f_{c\text{-FSB}}$ = 2.3 ksi < 0.6 f'_c

Service III - Midspan
- Bottom Flange: $f_{c\text{-FSB}}$ = -0.12 ksi < $0.095\sqrt{f'_c}$

Strength I - Midspan
- Compression controlled, ϕ = 0.75
- $\phi M_n = 970.3$ k-ft > $M_u = 879$ k-ft
- No need to verify min reinforcement

Shear forces – At ends
- Straight strands, $V_p = 0$
- Bonded strands, ϕ = 0.90
- Transverse rebar strain limited to 0.004
- Concrete contribution $\phi V_c = 280.3$ k
- $\phi V_n = 208.3$ k > $V_u = 130.3\ k$
- Since $V_u > 0.5\ \phi V_c$, provide min reinforcing
- Min reinforcement satisfies interface shear
- Additional longitudinal reinforcement due to vertical shear is not required

Construction Activities

Schedule

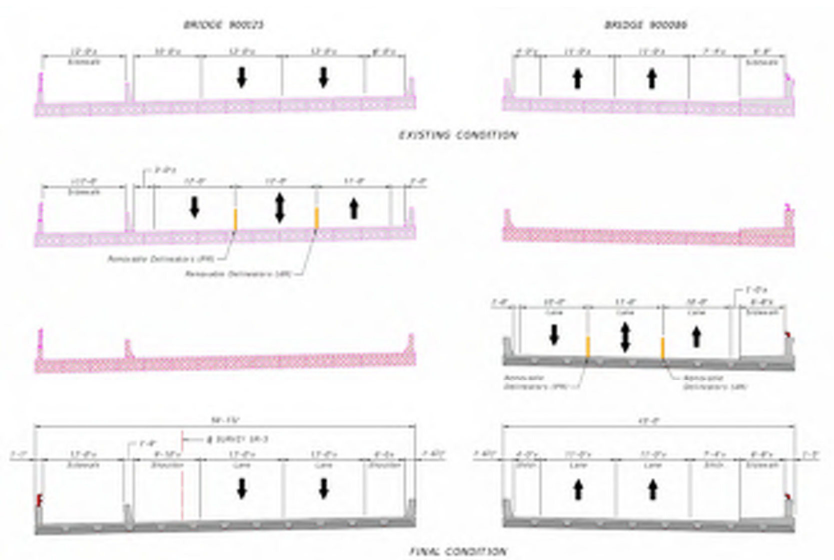
Construction Timeline

- Kiewit Infrastructure South; 6.17 Million (10/31/2019) & 167 days
- Construction started on March 16, 2020
- Reversible lanes were implemented on April 15, 2020 -- Bridge 900086 was closed to traffic
- Traffic shift on Bridge 900125 was at 10 am; relocation of delineators took 20 minutes
- Traffic was shifted to newly built 3-spans of Bridge 900086 on 7/6/2020
- Traffic shift on Bridge 900086 was at 2 pm; relocation of delineators took 20 minutes
- Bridge were open to two lane of traffic on 9/25/2020
- Anticipated completion day 11/12/2020

Construction Activities

Construction Sequence

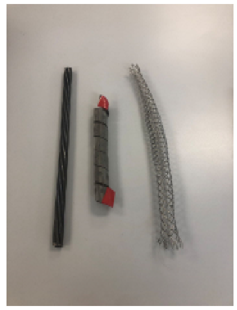
- Existing bridges have 2 lanes of traffic in each direction
- Carried out a traffic analysis during construction to allow an Innovative MOT scheme:
  - Maintains existing number of lanes in each direction during peak hours
- Reversible lanes during MOT – First Time application using flush-mounted removeable delineators on an arterial facility in the State
- Pedestrian traffic is maintained



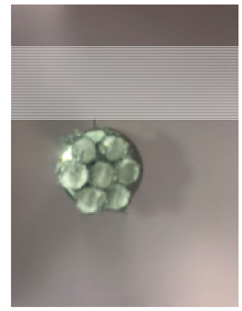
Construction Activities
Precast Plant

Rolls of CFRP

Mesh & braided grip



CFRP: 7 wire 0.6" strand



Construction Activities
Precast Plant

Wedges and couplers of CFRP and Standard prestressing steel

CFRP strand

Construction Activities

Precast Plant

CFRP prestress in casting bed

CFRP and Standard prestressing steel couplers layout

Prestressing steel

CFRP strands

Construction Activities

Precast Plant

CFRP prestressing & GFRP rebar inside form

GFRP Stirrups

CFRP strands

Construction Activities

Precast Plant

Cast FSBs

Construction Activities

Storage at Job Site

Delivery & Storage at Job Site

Construction Activities

FSB Erection

Erection of 2nd FSB

Erection of 3rd FSB

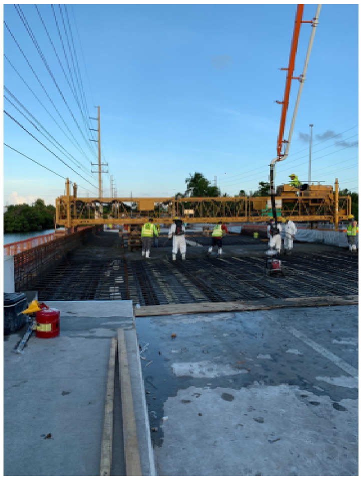
Construction Activities

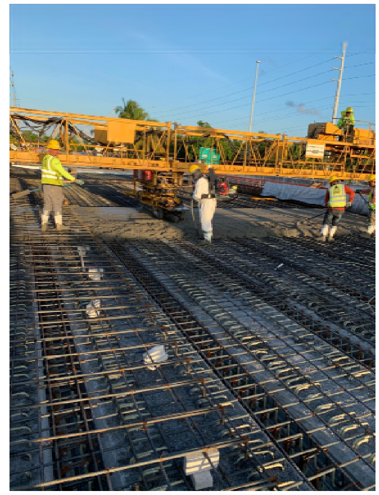
Deck Reinforcing Installation

Deck Reinforcing Installation

Construction Activities

Deck Pouring





Construction Activities

Reversible Lanes


Innovative MOT Concept in place from 4/15/2020 to 9/25/2020 - ZERO accidents

Construction Activities

Reversible Lanes

Bridges 900086 and 900125 open to regular traffic on 9/25/2020

For more information visit https://www.bpaengineers.com/successful-reversible-mot-at-cow-key/

Thank You

Presented by:
Luis M. Vargas, PhD, PE, SE

October 27, 2020

Field Applications of Non-Conventional Reinforcing and Strengthening Methods for Bridges and Structures, Part 2 of 3

Moderators: Antonio Nanni & Steven Nolan - *6 x 16 min. presentations + 3 min. Q&A each.*

10:05 am **An Introduction to GFRP Rebar and Recent International Field Applications -** Peter Renshaw *(Pultron Composites)*

10:24 am **Recent Canadian Developments on Non-Conventional Reinforcing for Concrete Structures, Design Codes, and Applications in Buildings and Bridges -** Brahim Benmokrane *(University of Sherbrooke)*

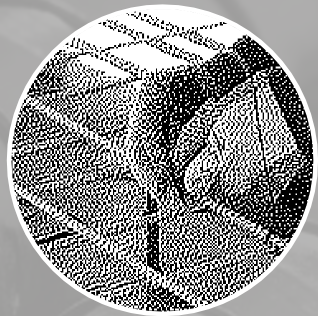
10:43 am **3-Span GFRP-RC Flat-Slab Bridge and Novel Seawall over Ibis Waterway**
Sybille Bayard *(CONSOR Engineers)*

11:02 am **5,000 ft. GFRP-RC Seawall Protects Highway A1A along Flagler Beach**
Christian Steputat *(University of Miami)*

11:21 am **Next Generation GFRP Bar Properties and Bridge Implementation Economics -** Doug Gremel *(Owens Corning Infrastructure Solutions)*

11:40 am **6-Span CFRP-PC/GFRP-RC Bridge over Placido Bayou**
Chris Gamache (CARDNO)

mateenbar™



Introduction to GFRP Rebar & Recent Field Applications

Pete Renshaw
Pultron Composites Ltd
Mateenbar Ltd

Why do we need an alternative Rebar?

The use of Steel Rebar has a long history

It is the standard method of reinforcing concrete structures

It is appropriate for more than 90% of applications

But, what about the other 10% ?

What do we use for the Other 10%

There are some applications where steel is not the best reinforcement

Currently, many architects & engineers are not aware that there are alternatives to steel rebar

So, they continue to use steel

$$4\ Fe + 3\ O_2 \rightarrow 2\ Fe_2O_3$$

Iron Oxide (Rust) is larger than steel

Steel rebar expands as it rusts

Expansion of rebar causes Spalling

concrete structures to blow apart

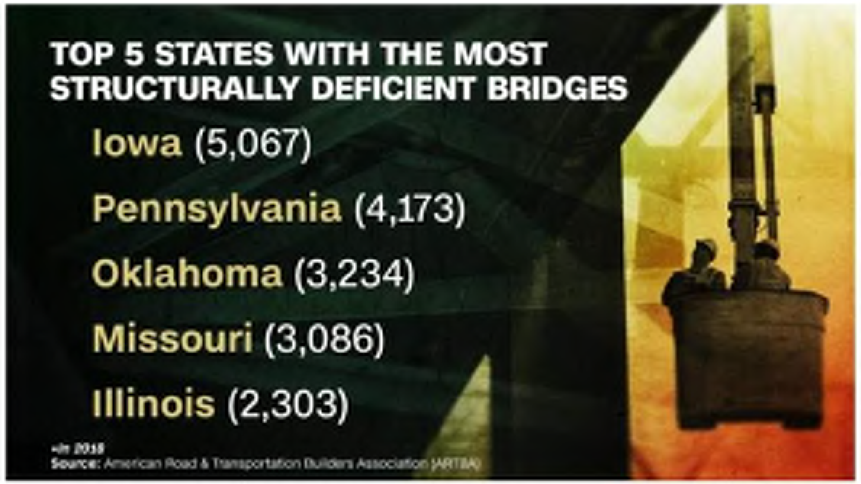
A **Very Expensive** Chemical Reaction

$4Fe + 3O_2 \rightarrow 2Fe_2O_3$ - $

CNN story from 2018

There are more than 54,000 bridges in the US in need of repair, says this study

By Mercedes Leguizamon and Saeed Ahmed, CNN
Updated 0010 GMT (0810 HKT) February 3, 2018



(CNN) — There are more than 54,000 bridges in the United States that need to be repaired or replaced. That's good news -- relatively speaking -- because a year ago, the number was more than 55,000.

The latest figure comes from a report by the American Road and Transportation Builders Association, a group that advocates for strong investment in transportation infrastructure.

Using data from the Federal Highway Administration, the group releases an annual Deficient Bridge Report.

A $1T Infrastructure Plan

37 Years to Repair or Replace

Many of these Bridges are failing due to Spalling of Concrete

GFRP rebar is a viable alternative

What is GFRP

GFRP - Glass Fibre Reinforced Plastic
Composite Material

GFRP Rebar

2 x tensile strength of mild steel

¼ the weight of steel

Non electromagnetic

Excellent Thermal Insulator

Cuttable

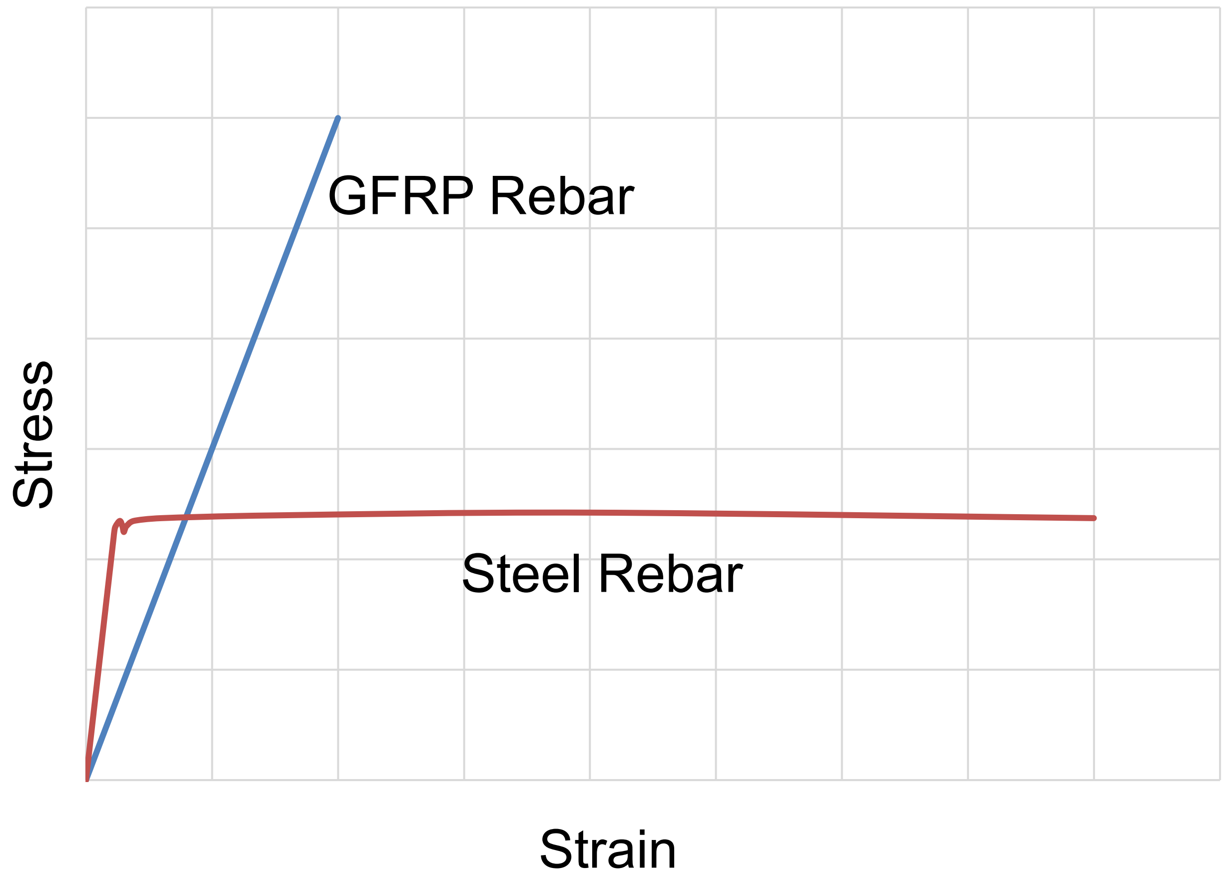
Non-metallic, so No Rust

Strength

Tensile Strength 145 ksi (1000 Mpa)

Tensile Modulus 5800 to 8700 ksi (40 to 60 GPa)

Elastic until Failure



Weight

¼ the weight of steel

1.5” bar at 20ft weighs less than 33 lb

Significant Labour Saving on Construction Site

Safety in High Voltage Areas

No Electromagnetic Induction

No Electrical Interference

Non Magnetic

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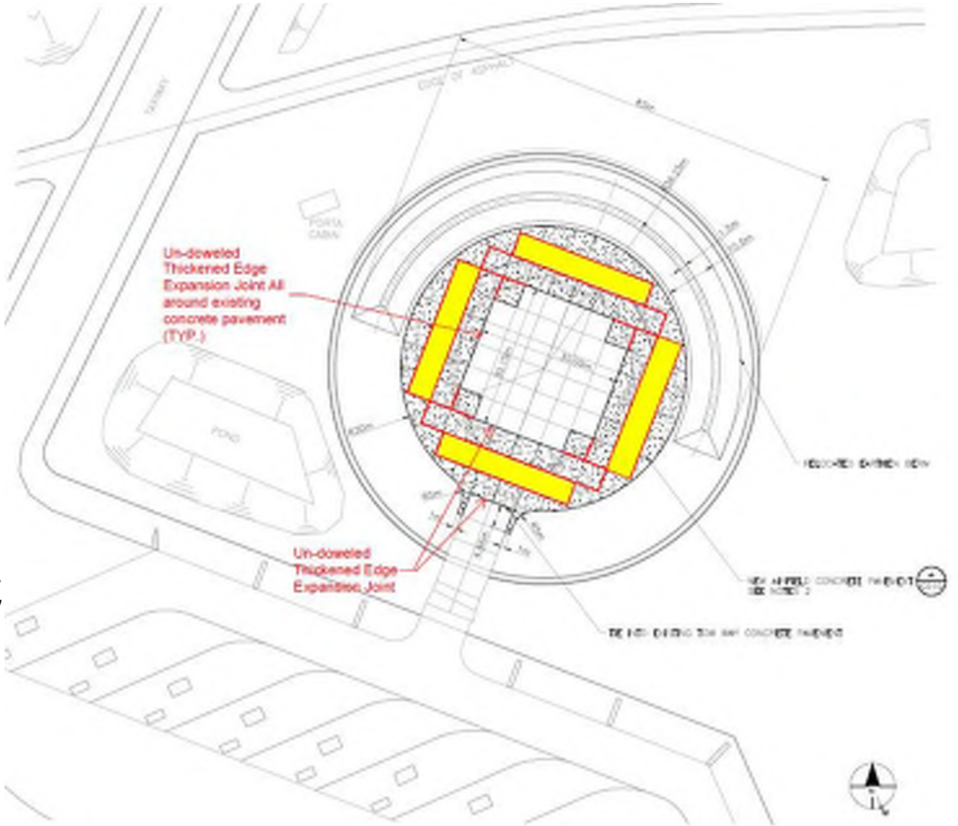
Aircraft Compass Calibration Pads

Calibration & Housing of Sensitive Electromagnetic Equipment



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Insulated Concrete Sandwich Panel Construction

Homes & Industrial

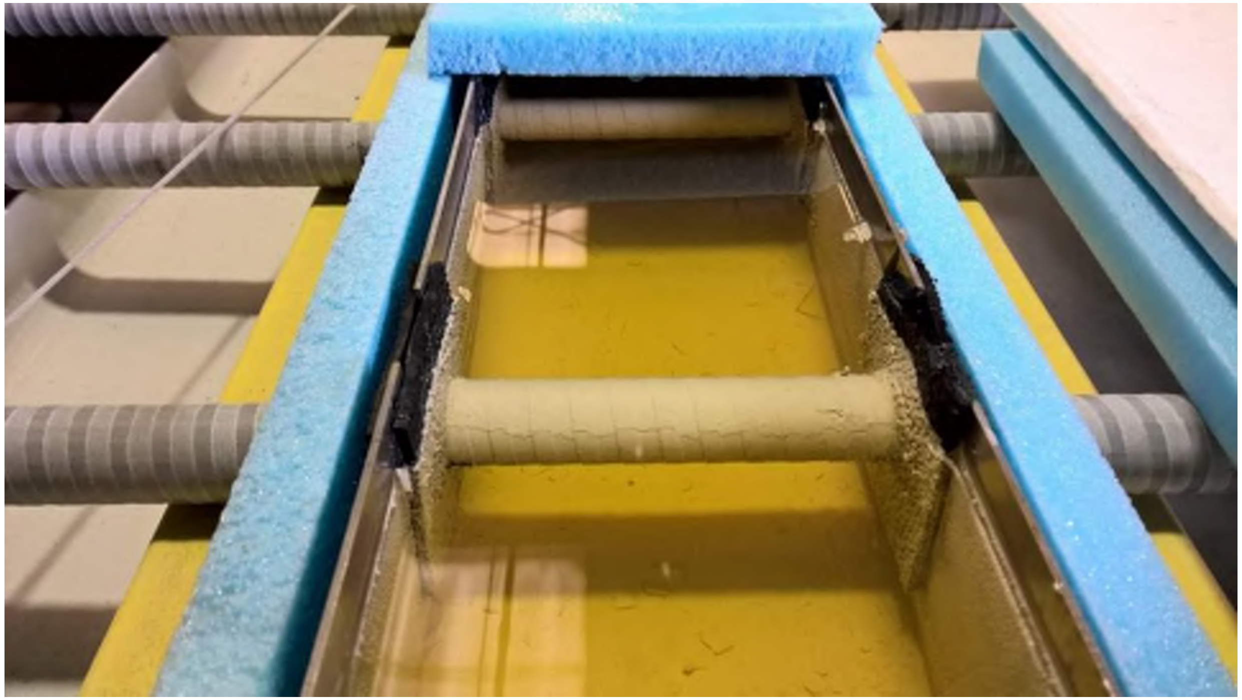
Soft Eyes for Tunnels

Non Metallic – No Rust

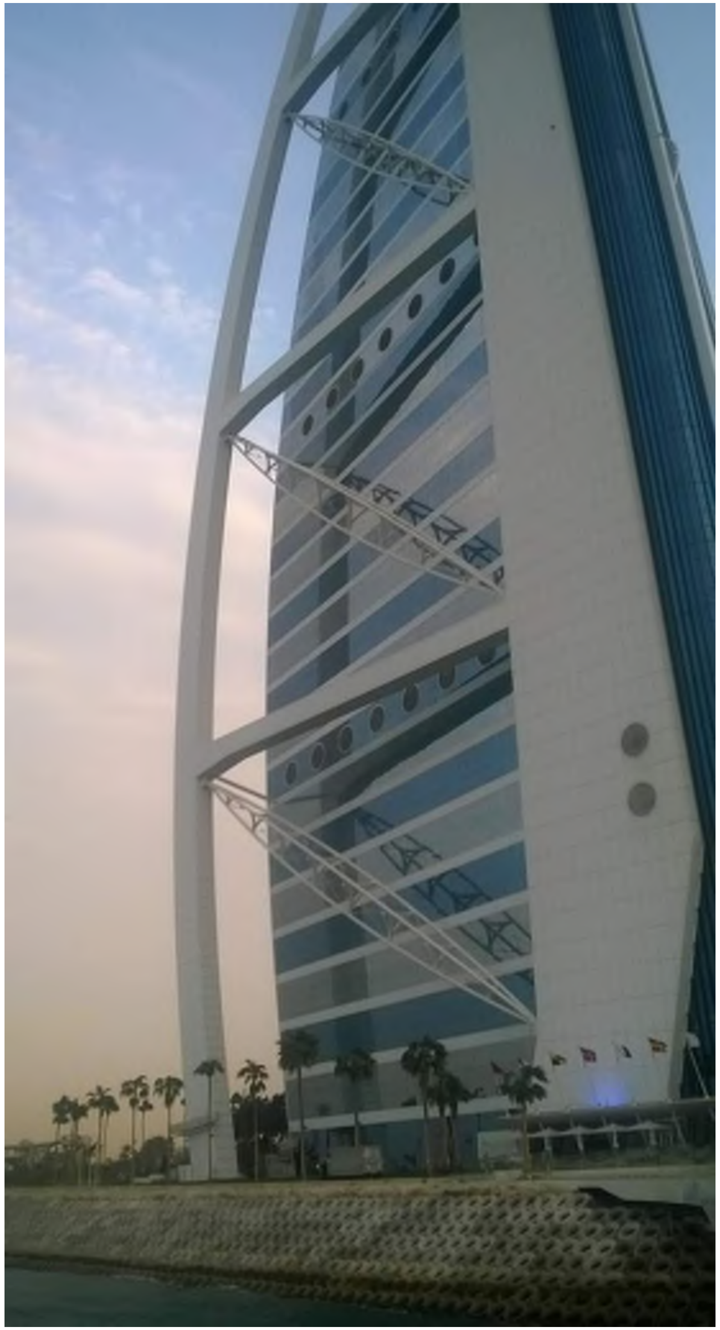
Steel Rebar Begins to Rust Even Before Concrete is Poured

ACI 440.3R – Accelerated Durability Test

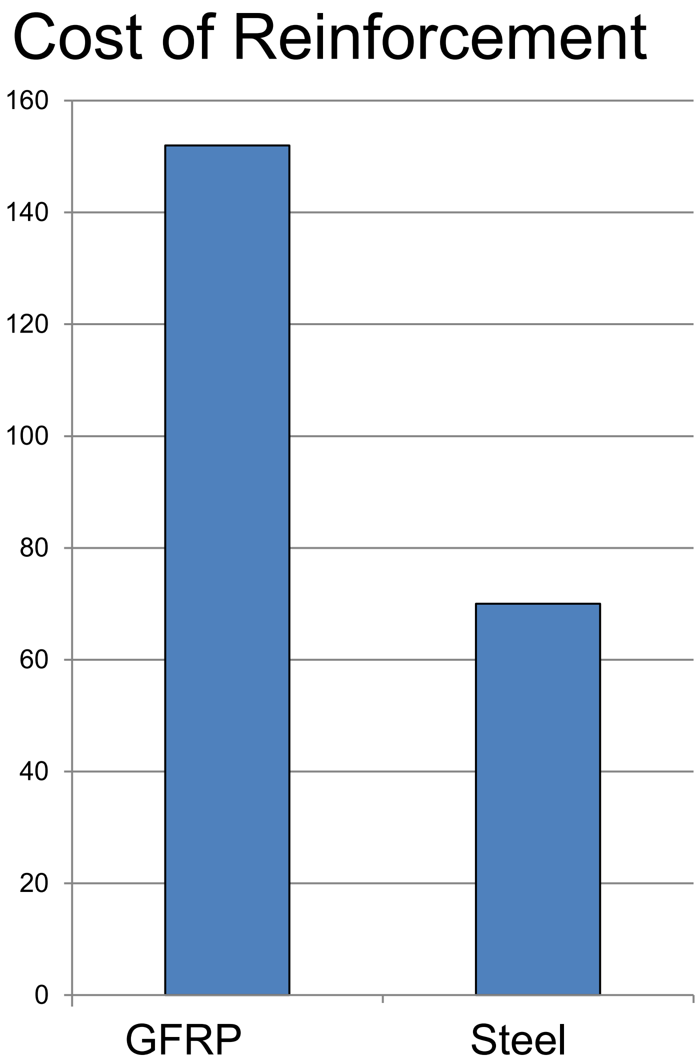
96% Tensile Strength Retained after equivalent of 100 Years

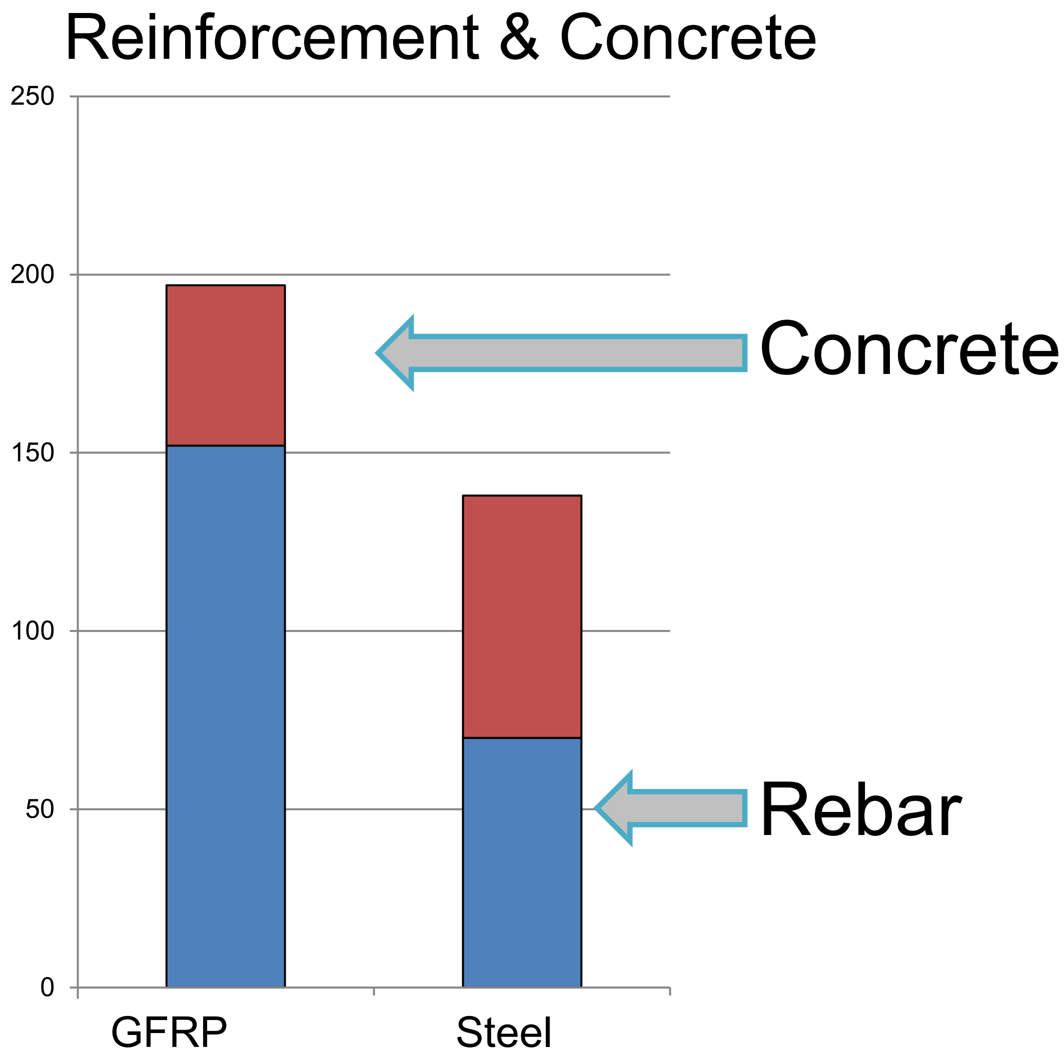


GFRP Rebar in Harsh Environments



Cost Comparison - Materials





Material Costs cont'd

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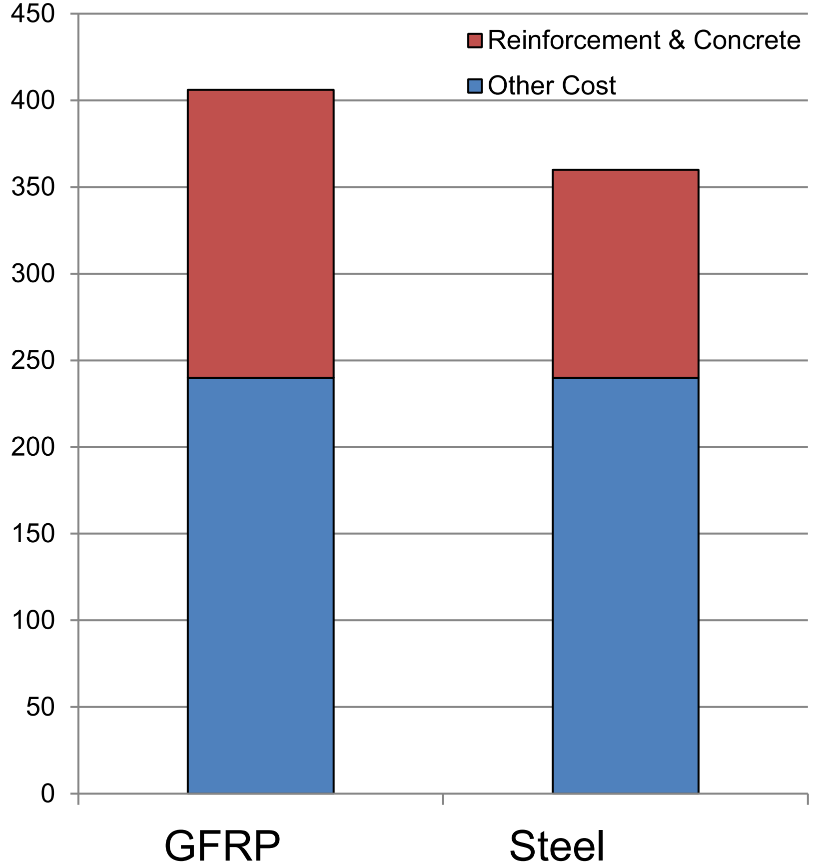
Example (Middle East)

Total cost comparison.
2mx2m panel



Concrete used with GFRP is 30MPa (corrosion resistance not required) @ AED200/m^3

Concrete used for steel reinforcement is 50MPa concrete @ AED300/m^3

Concrete Savings helps offset GFRP cost

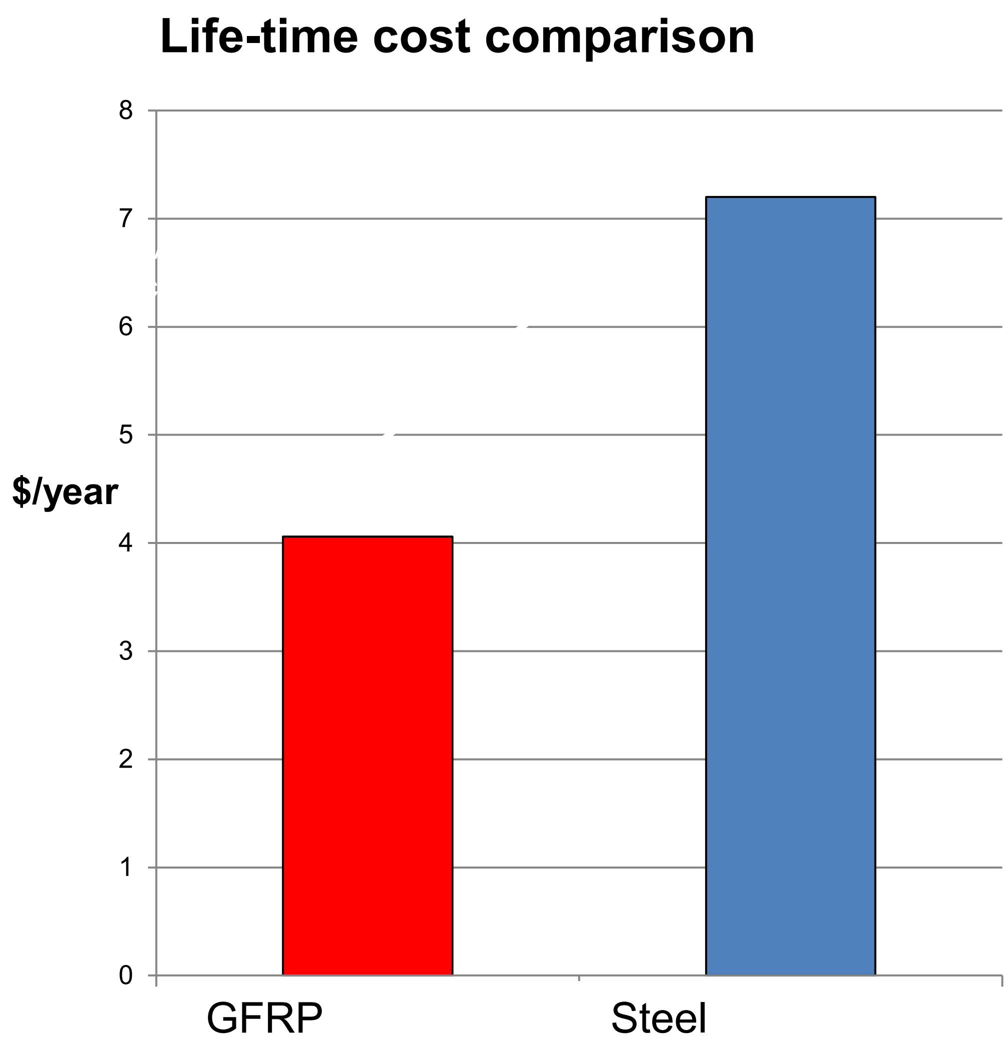
Total Difference = 7%

Whole of Life Costs

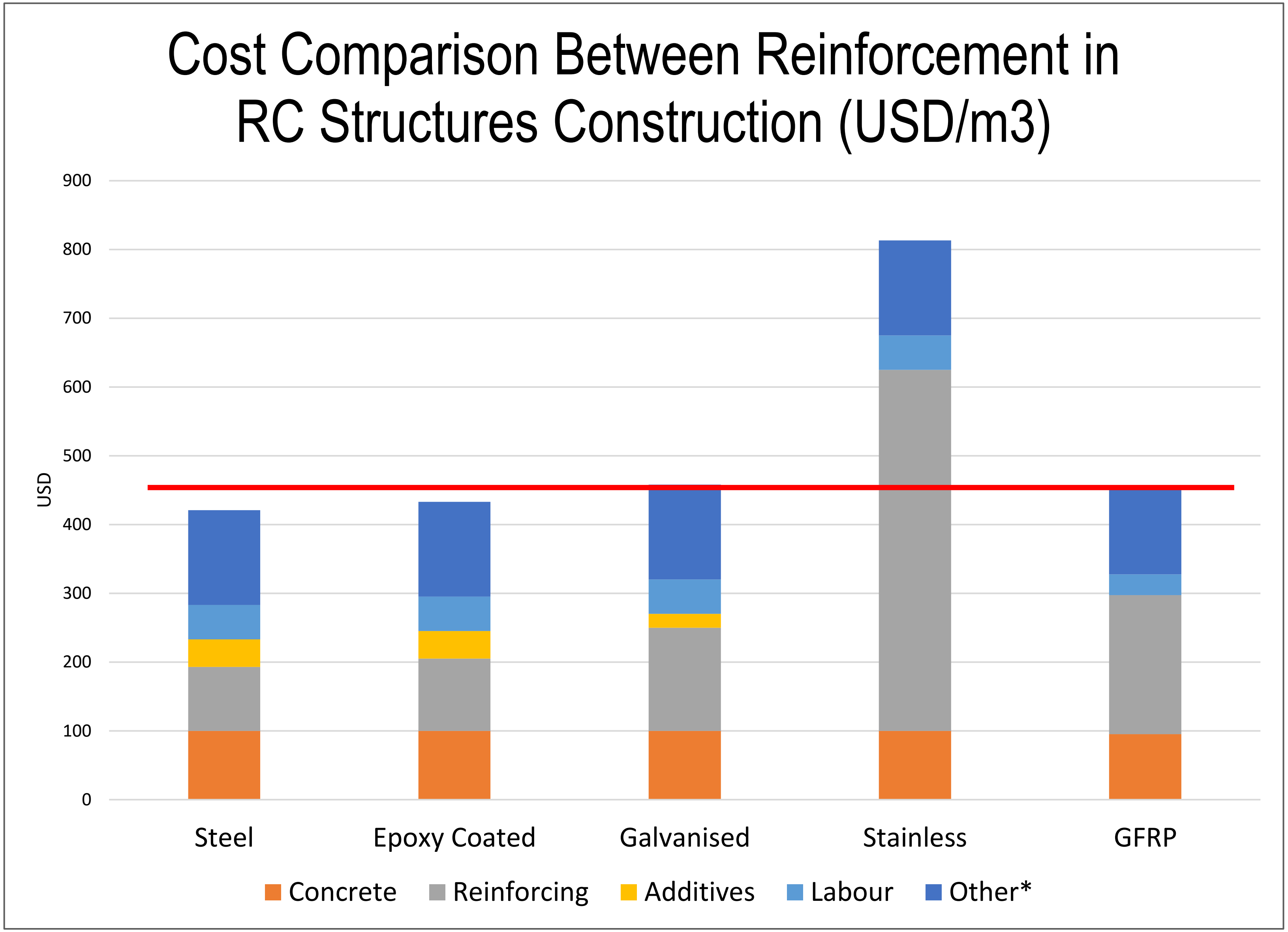
Total Cost Difference = 7%

GFRP rebar increases asset lifespan

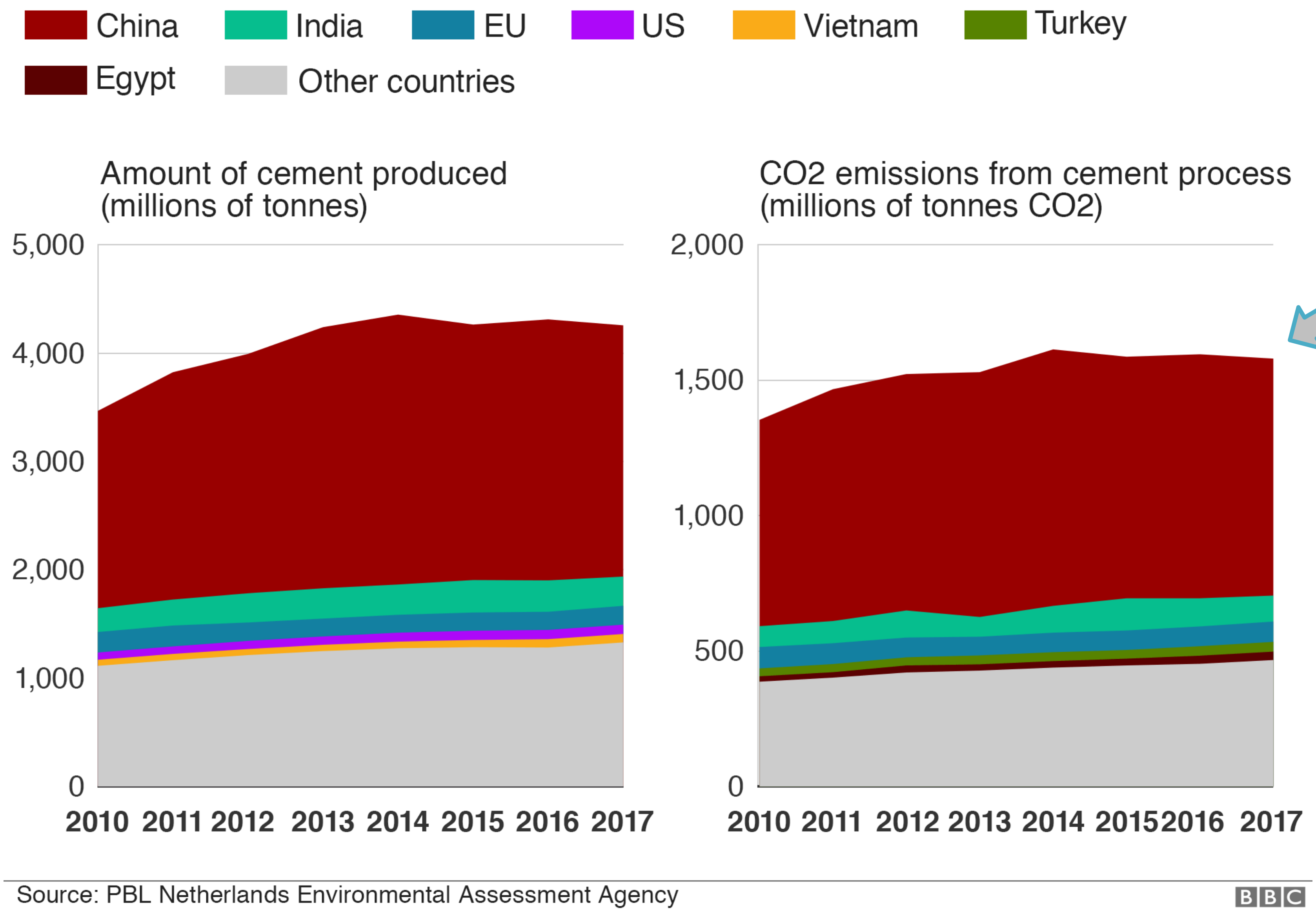
Real Cost of GFRP is effectively lower as asset value is retained



Cost Comparison of Reinforcement Types

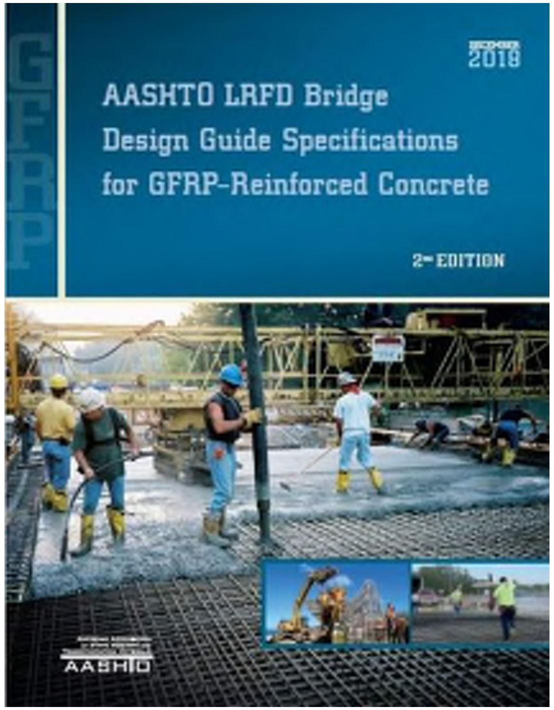


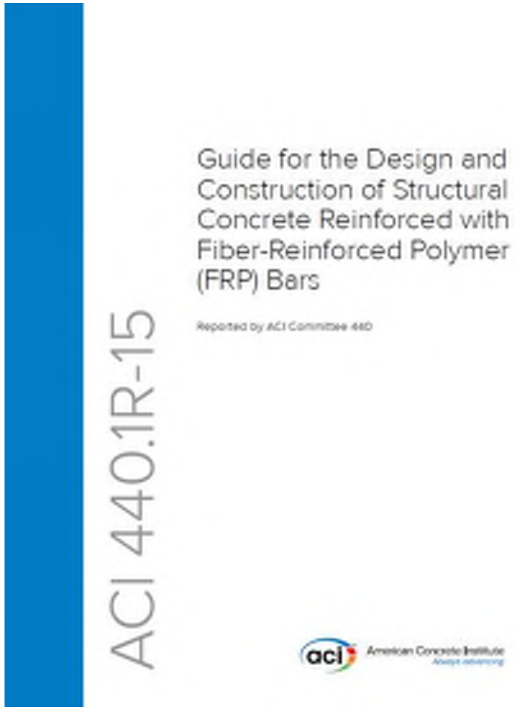
Environmental Considerations

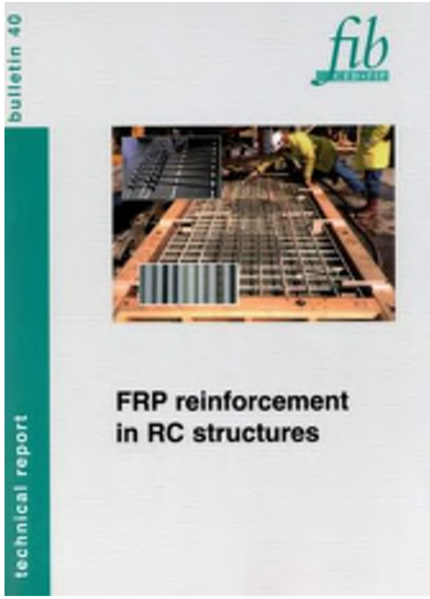


> 1500 Million tonnes of CO_2 p.a.

Codes & Guides

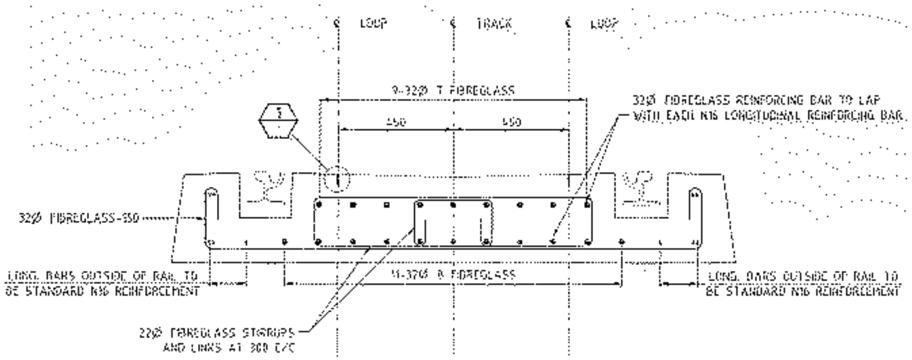







DOH

Rail Detection Loops, QLD, Australia



Toll Plaza, Turnpike, Maine

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YAS Island Formula 1 Track, UAE

NATO, Afghanistan





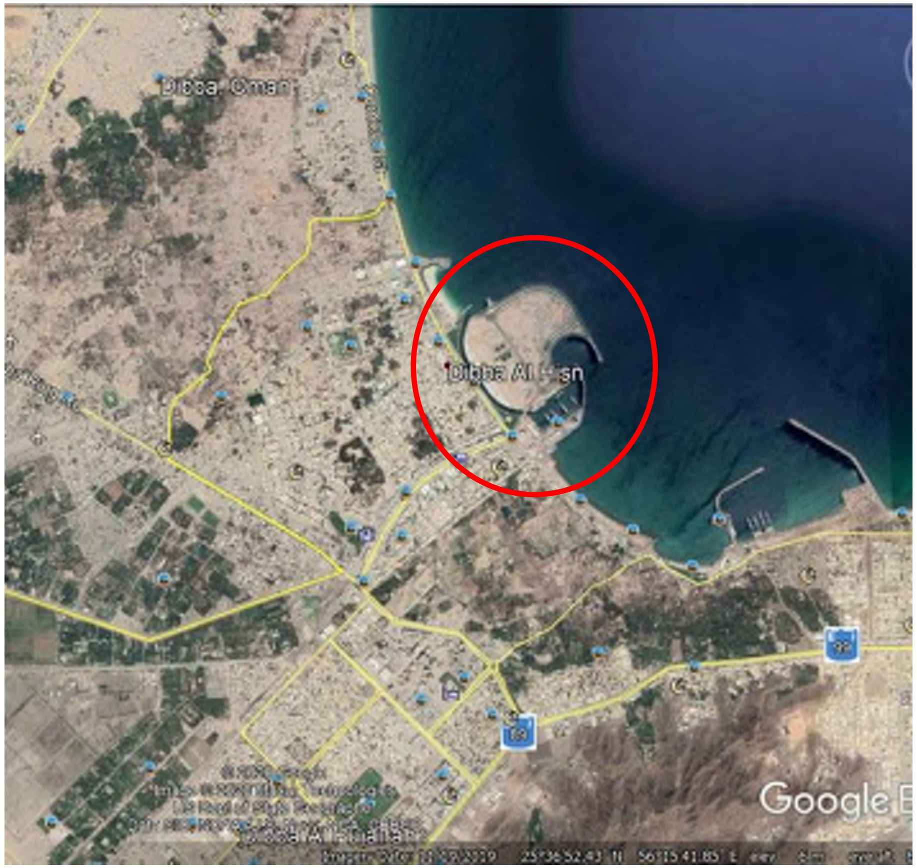

Northside Storage Tunnel, Sydney

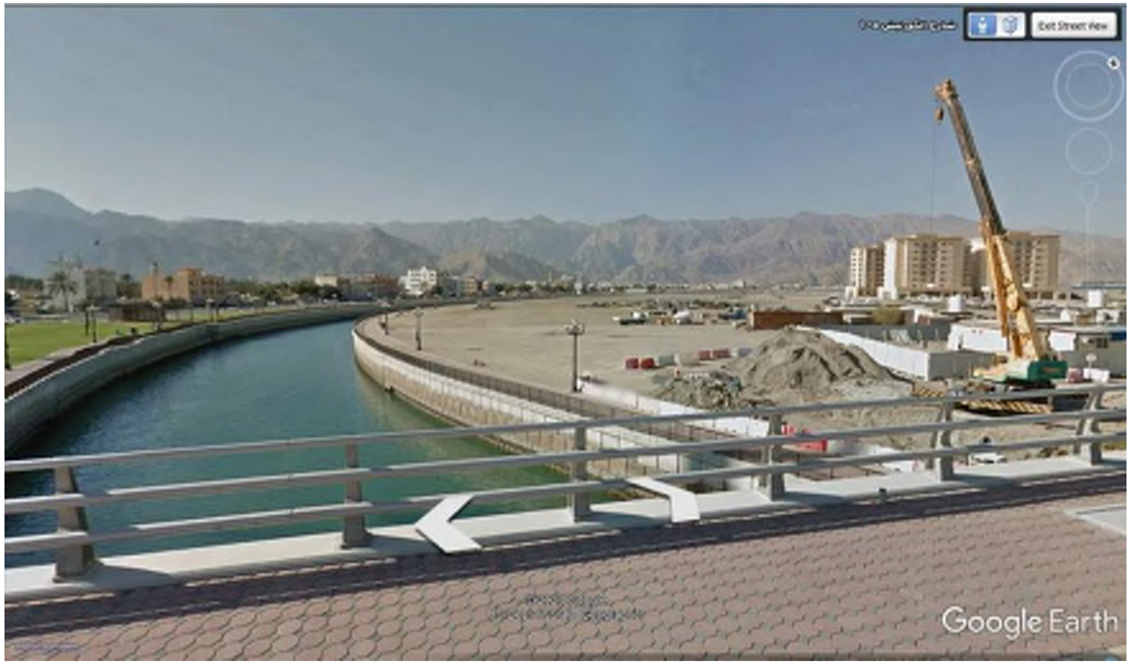
Potash Plant, Jordan

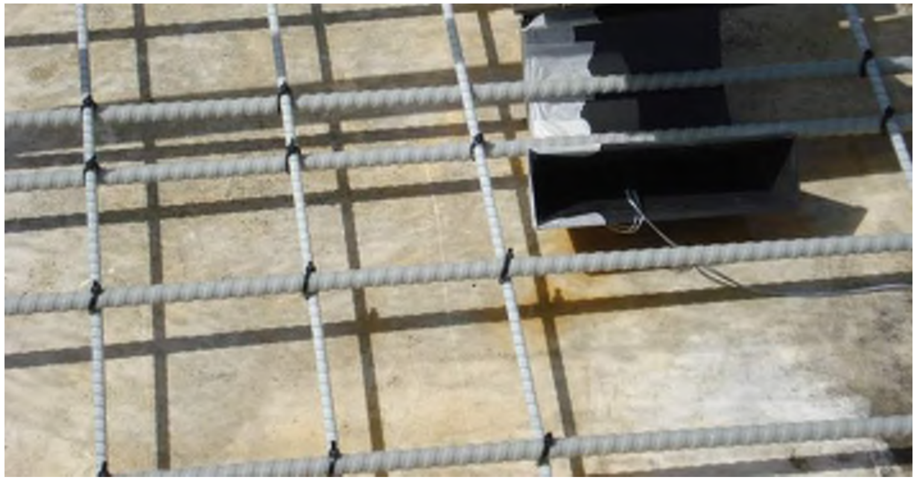
Kwinana Desalination Plant, WA, Australia

Terminal 4, Jebel Ali Port, UAE

Sea wall Dibba, United Arab Emirates







Interstate I5, Washington, USA

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State Highway and Railway Repair, Kaikoura

Flood Mitigation Channel, Jazan, KSA

Sculpture, UAE

Schools on Pacific Atolls, Marshall Islands

GFRP is a Genuine Alternative to Steel

- ✓ Cost Effective
- ✓ Proven History
- ✓ Codes & Guides
- ✓ Ideal for Challenging Environments

Further Information

Thank You

Further information available at
www.mateenbar.com

Questions

ACI Fall 2020 Virtual Convention

October 28th 2020, 9:30am – 2:30pm, Virtual

Recent Canadian Developments related to Unconventional Reinforcing for Concrete Structures, Design Codes, and Applications in Buildings and Bridges

Dr. Brahim Benmokrane, P. Eng.

FRSC, FACI, FCSCE, FIIFC, FCAE, FEIC, FBEI

Professor of Civil Engineering

Canada Research Chair in Advanced Composite Materials for Civil Structures
NSERC/Industrial Research Chair in Innovative FRP Reinforcement for Concrete
Director, Sherbrooke University Research Centre on FRP Composites (CRUSMAC)

University of Sherbrooke, Sherbrooke, QC, CANADA

E-mail:Brahim.Benmokrane@usherbrooke.ca

Co-authors:

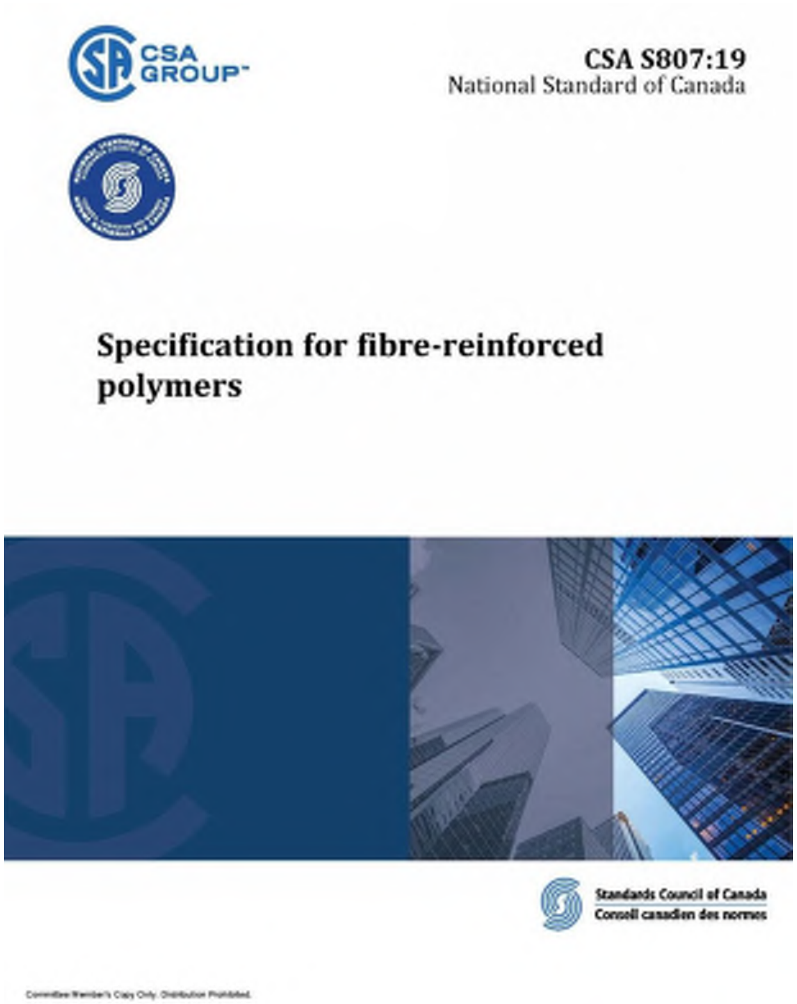
Hamdy Mohamed, Khaled Mohamed, and Salaheldin Mousa

Outline of presentation

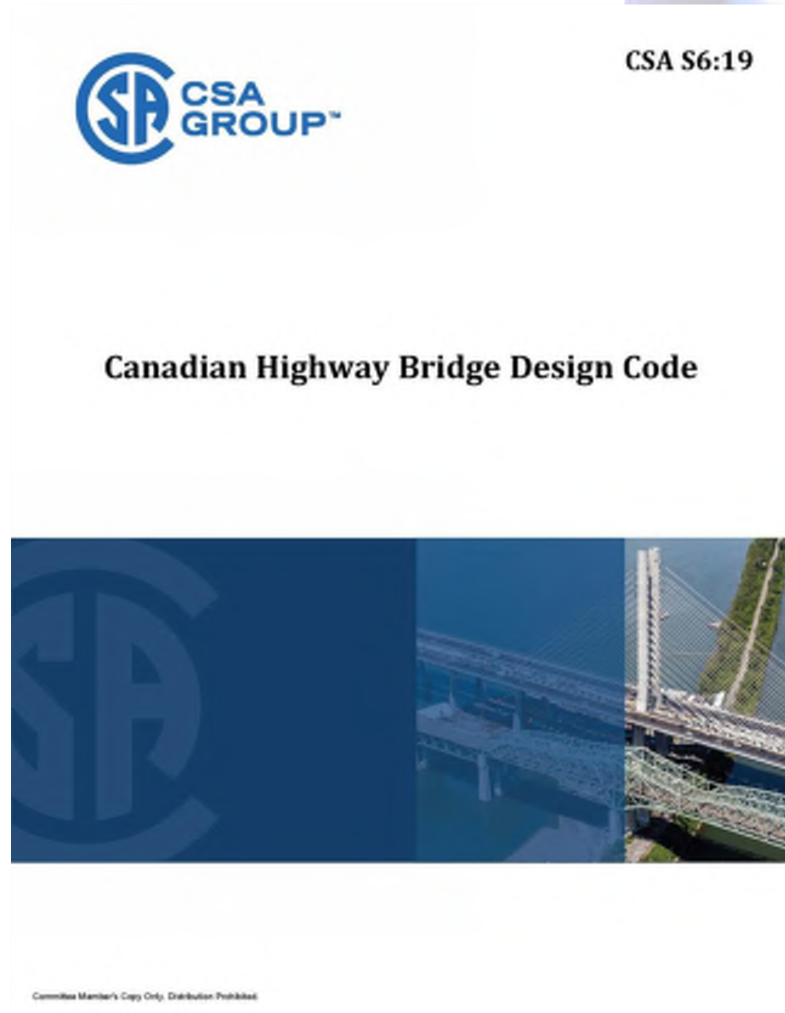
- <u>New Editions</u> of CAN/CSA Standards & Specifications : CSA S807-19 and CSA S6-19
- Introduction- FRP Reinforcement in Canadian Codes and Standards: <u>Recent Developments</u>
- <u>Recent Application</u> of GFRP reinforcement in Infrastructures

New Editions of CAN/CSA Standards & Specifications : CSA S807-19 and CSA S6-19

FRP Recent CSA Standards & Specifications



CSA S807-19



CSA S6-19

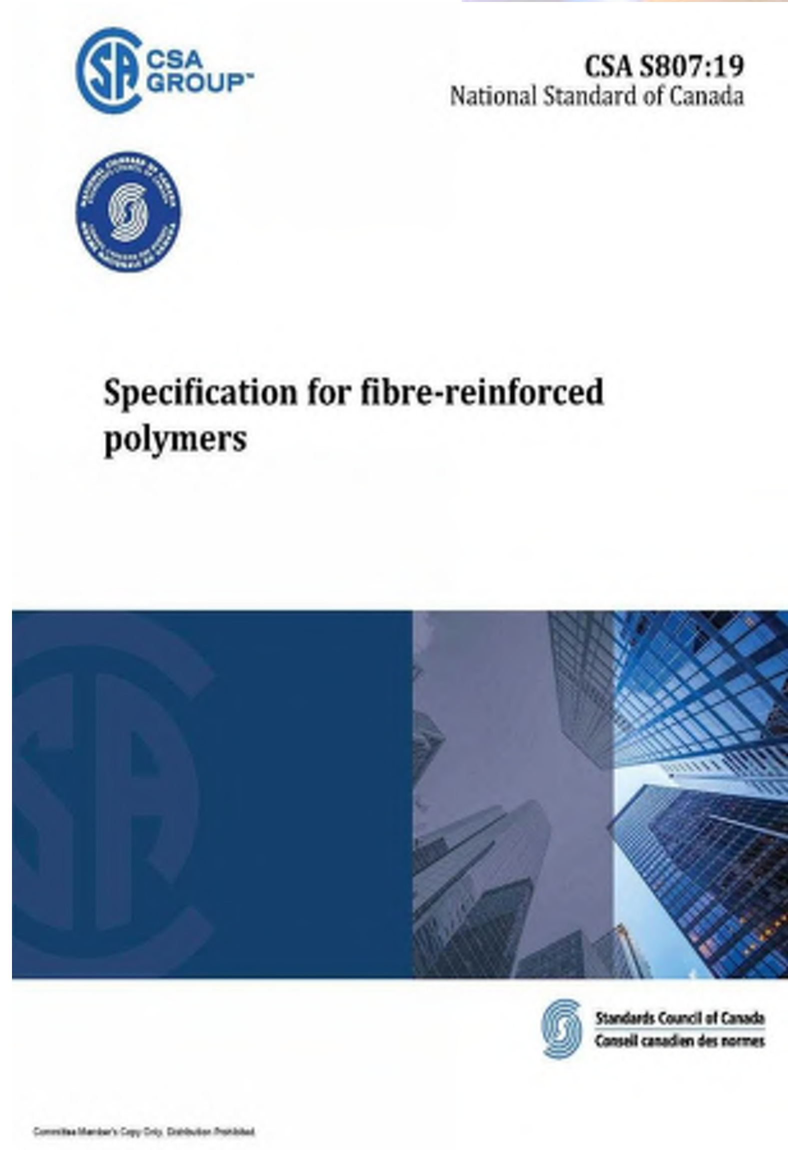
HOW TO CERTIFY/QUALIFY/SPECIFY FRP BARS

New Edition of CSA S807 (2019)

The most comprehensive specs for FRP rebars in the world

CSA S807

- First edition in 2010
- Re-approved in 2015
- New Edition in 2019 (Second Edition)



CSA Material Specifications (CSA S807)

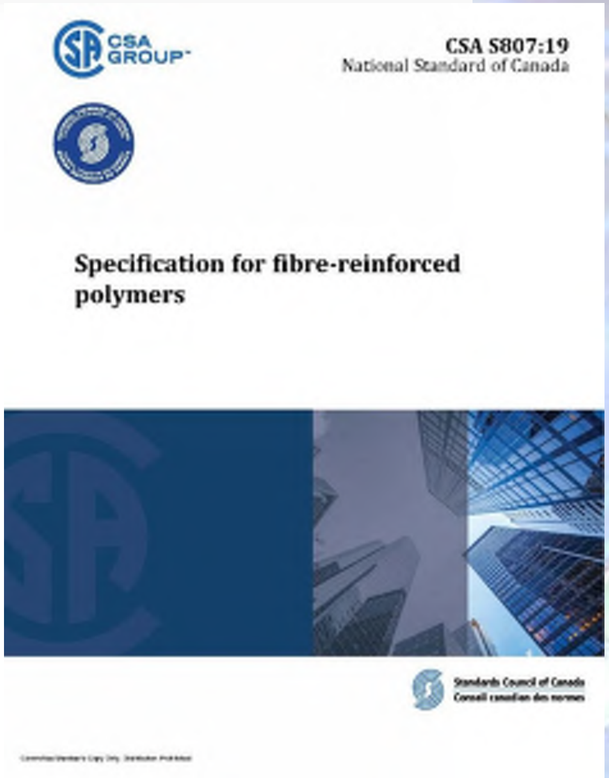
Describes permitted constituent materials, limits on constituent volumes, and minimum performance requirements.

Provides provisions governing testing and evaluation for product qualification and QC/QA.

CSA S807:19 Specifications for fiber reinforced polymers Recent Modifications

Changes to this edition of S807 include the following:

- change to the scope of the Standard to include material properties of FRPs and the introduction of basalt fibers and specification of E-CR glass;
- addition of fine aggregate for sand coating; and
- addition of production lot size for straight, bent, and anchor-headed bars.


CSA GROUP
CSA S807:19
National Standard of Canada

Specification for fibre-reinforced polymers

Standards Council of Canada
Conseil canadien des normes

CSA S807:19 Specifications for fiber reinforced polymers Recent Modifications

4.2.2.1

The manufacturer shall define the production lot size for the production method used for the FRP (e.g., by weight, area of cross-section, and linear measurement). The manufacturer shall record values for the amounts of materials used in each lot. The production lot size of straight bars shall be divided in sub-lots of 20 000 m of bars up to a maximum of 60 000 m of bars of the same diameter. The manufacturer's quality control tests and samples shall be in accordance with Tables 7 and 8 for the first sub-lot of 20 000 m of bars of each production lot. For the two subsequent sub-lots of 20 000 m each, the manufacturer's quality control tests shall include

a) fibre content;
b) glass transition temperature;
c) cure ratio;
d) water absorption for one week; and
e) apparent horizontal shear strength.

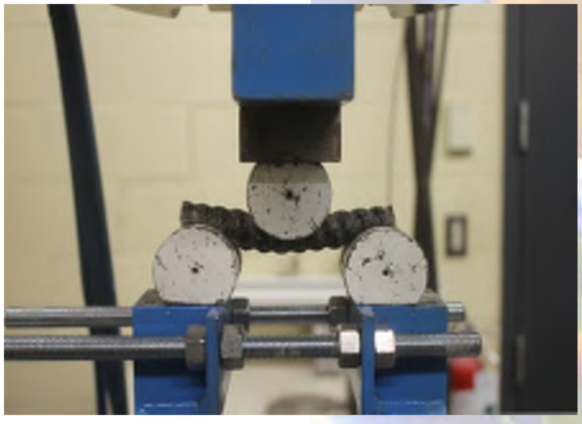


Table 7 (Concluded)

Property	Number and details of test specimens required: Qualification test	Manufacturer's QC	Owner's QA	Provided if needed for special applications†	Test method	Specified limits
Apparent horizontal shear strength by the short-beam method*	24 tests from 3 production lots for 10, 13, 15, 20, 25, and 32 mm or only the sizes manufactured by the supplier	5 tests for each bar size per lot used on project	5 tests for each bar size per lot used on project	N/A	ASTM D4475	≥ 35 MPa for Grade I bars ≥ 40 MPa for Grade II bars ≥ 45 MPa for Grade III bars
Apparent horizontal shear strength in high pH solution at 60 °C (alkali resistance)*	24 tests from 3 production lots for 10, 13, 15, 20, 25, and 32 mm or only the sizes manufactured by the supplier	N/A	N/A	N/A	ASTM D4475 Test duration: 3 months	The average from testing shall not be less than 85% of the average from room temperature testing for qualification (Table 7).

CSA S807:19 Specifications for fiber reinforced polymers
Recent Modifications

Table 9
Minimum pullout capacity of anchor-headed bars
(See Table 7.)

Fibre	Diameter, mm	Minimum pullout capacity, kN	Slip at loaded end limits
Glass	15	100	At 100 kN no more than 0.5 mm
	20	120	At 100 kN no more than 0.5 mm

Table 7 (Concluded)

	Number and details of test specimens required					
Property	**Qualification test**	**Manufacturer's QC**	**Owner's QA**	**Provided if needed for special applications†**	**Test method**	**Specified limits**
Pullout capacity of anchor-headed glass fibre-reinforced polymer bars	24 tests from 3 production lots for 15 and 20 mm or only the sizes manufactured by the supplier	N/A	N/A	5 tests on bar size requested	ASTM D7913/D7913M A 300 × 300 × 300 mm concrete block shall be used.	Minimum values defined in Table 9.
Durability characteristic of anchor-headed glass fibre-reinforced polymer bars	24 tests from 3 production lots for 15 and 20 mm or only the sizes manufactured by the supplier	N/A	N/A	5 tests on bar size requested	Test method in Annex F	The average from testing shall not be less than 80% of the average unconditioned testing for qualification (this Table).

CSA S807:19 Specifications for fiber reinforced polymers
Recent Modifications

Production lot size of Straight bars

The production lot size of straight bars shall be divided in sub-lots of 20,000 m of bars up to a maximum of 60,000 m of bars of the same diameter.

QC tests as indicated in Tables 3 and 4 for the first sub-lot of 20,000 m.

For the two subsequent sub-lots of 20,000 m each, the QC tests shall include:

- fibre content;
- glass transition temperature;
- cure ratio;
- water absorption for one week; and
- apparent Horizontal Shear Strength.

CSA S807:19 Specifications for fiber reinforced polymers
Recent Modifications

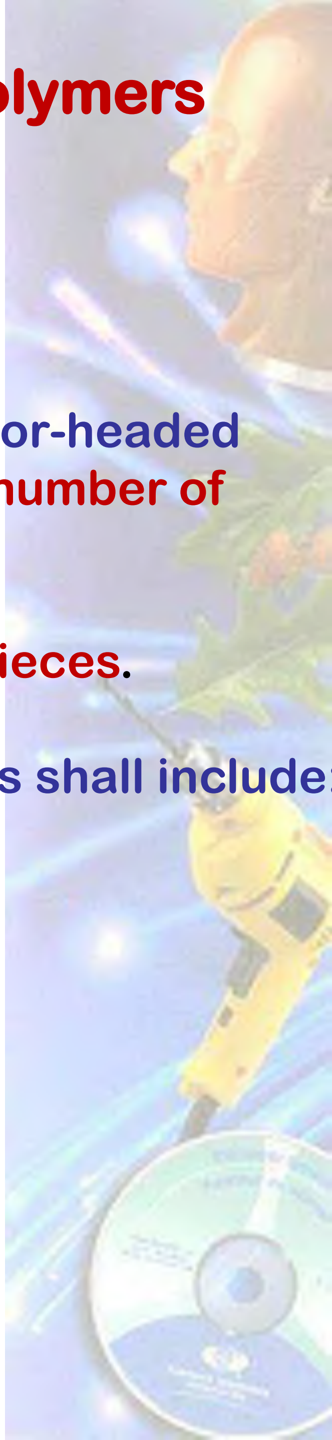
Production lot size of bent bars

The production lot size of bent bars of congruent shape and anchor-headed bars shall be divided in sub-lots of 2000 pieces up to a maximum number of 6000 pieces.

QC tests as indicated Tables 3 and 4 for the first sub-lot of 2000 pieces.

For the subsequent two sub-lots of 2000 pieces each, the QC tests shall include:

- fiber content;
- glass transition temperature;
- cure ratio;
- water absorption for one week; and
- apparent Horizontal Shear Strength.



CSA S807:19 Specifications for fiber reinforced polymers
Recent Modifications

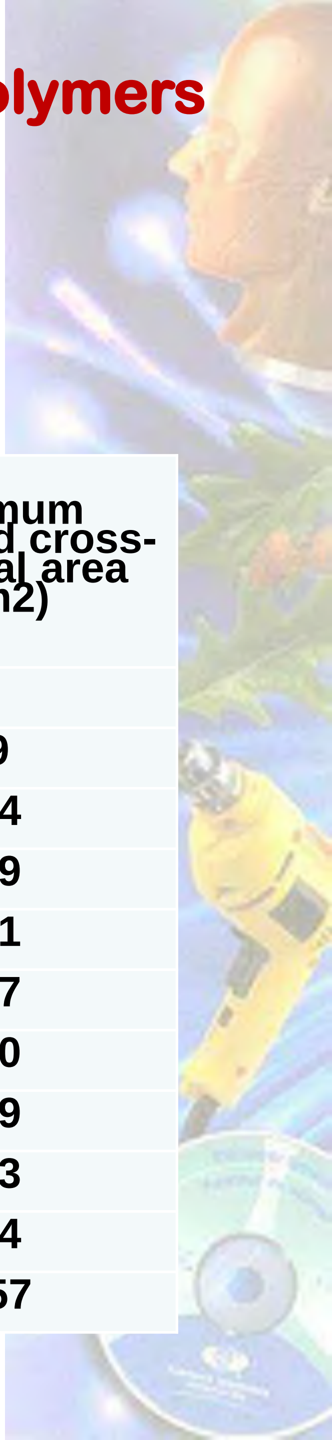
- **Alkali resistance in high pH solution (without load), the tensile capacity retention ≥ increased from 80% to 85% UTS.**

- **Alkali resistance in high pH solution (with load), the tensile capacity retention ≥ increased from 70% to 75% UTS.**

CSA S807:19 Specifications for fiber reinforced polymers
Recent Modifications

Table 1A
Designated Bar Diameter and Nominal Area
(Same as ASTM D7957/D7957M – 17)

Diameter mm	Nominal cross-sectional area (mm2)	Minimum measured cross-sectional area (mm2)	Maximum measured cross-sectional area (mm2)
8	50	48	79
10	71	67	104
13	129	119	169
15	199	186	251
20	284	268	347
22	387	365	460
25	510	476	589
30	645	603	733
32	819	744	894
36	1006	956	1157



CSA S807:19 Specifications for fiber reinforced polymers
Recent Modifications

Minimum Tensile Strength for GFRP Rebars (Grade III)

Minimum tensile strength for straight bars (#4 to #8) :
1000 MPa (145 ksi)

Minimum tensile strength for straight portion of bent bars (#4 to #8) :
1000 to 850 MPa (145 to 125 ksi)

Minimum tensile strength for bent portion of bent bars (#4 to #8) :
450 to 390 MPa (65 to 57 ksi)

CSA S807:19 Specifications for fiber reinforced polymers
Recent Modifications

Table 6
Grades of FRP bent bars corresponding to their minimum modulus of elasticity of the straight portion, GPa
(See Clauses 8.3 and 10.1 and Table 7.)

	Grade IB	Grade IIB	Grade IIIB
Designation	**Individual bars**	**Individual bars**	**Individual bars**
AFRP	50	60	65
BFRP	50	55	60
CFRP	80	100	120
GFRP	40	45	50

Annex E (normative)
Method of test for determining the strength of the bent portion of FRP reinforcing bars

Note: *This Annex is a mandatory part of this Standard.*

E.1 Scope

E.1.1
This test method is used to determine the force in the straight portion of a bent fibre-reinforced polymer (GFRP) bar, used as internal reinforcement for concrete structures, when rupture occurs in the bend.

Annex E (normative)
Method of Test for Determining the Strength of the Bent Portion of FRP Reinforcing Bars

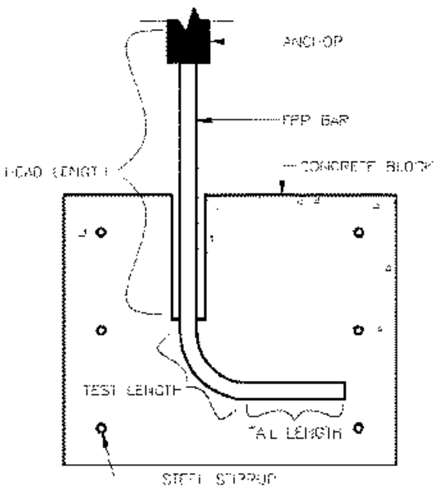


Figure 1 – General Arrangement

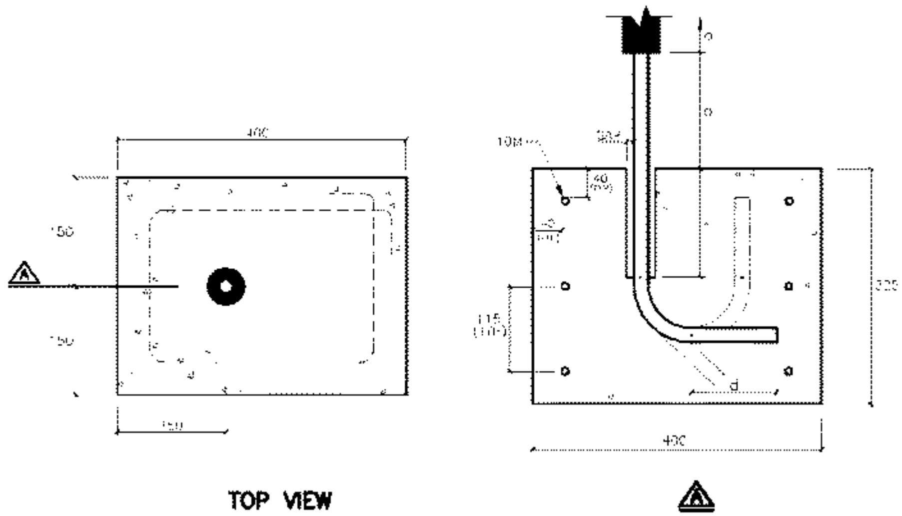


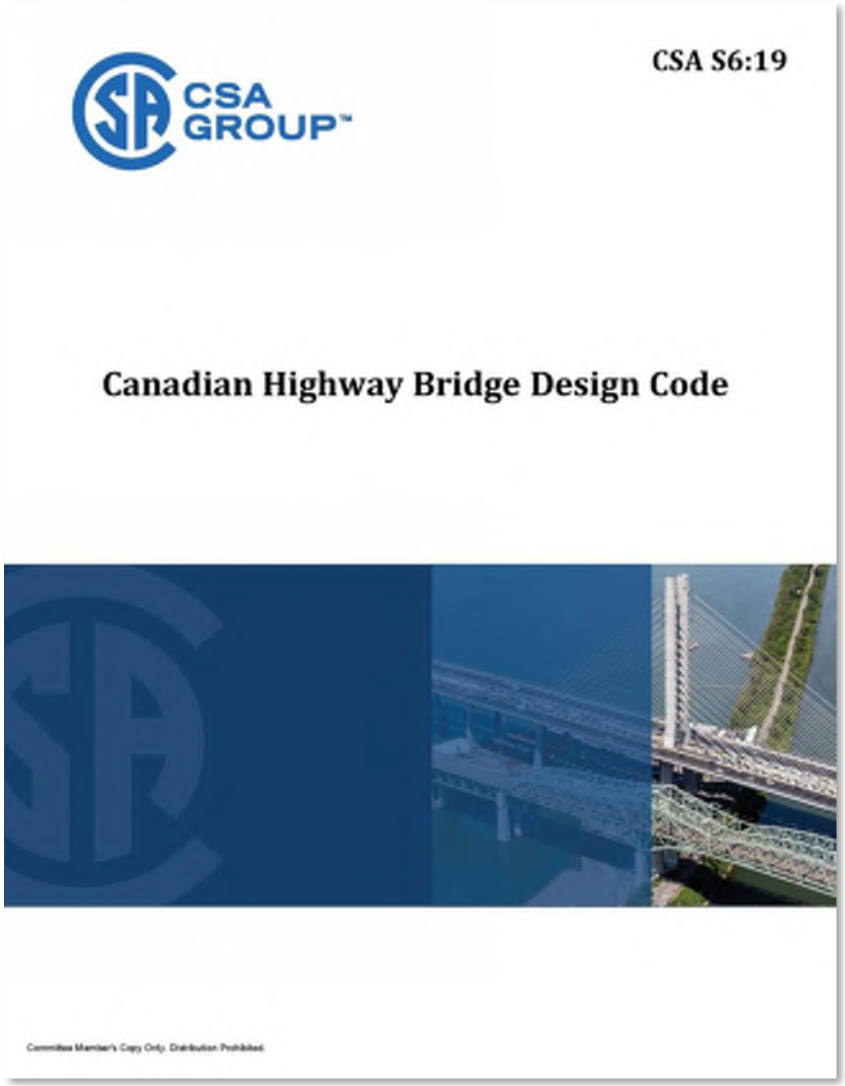
Figure 2 – Dimensional Arrangement of the Block
(nominal diameter of 20 mm or less, bent at an angle between 0 and 180 degrees, and manufactured with a bend-radius-to-bar-diameter ratio of 4 or less)

CSA S807:19 Specifications for fiber reinforced polymers
Recent Modifications

GFRP #5 Lot #	Ultimate Load (kN)	Ultimate Stress (MPa)	Tensile Modulus (GPa)	Ultimate Strain (%)
1	335	1180	63	1.9
2	307	1082	62	1.8
3	318	1118	64	1.7

GFRP #6 Lot #	Failure load (kN)	Bend Strength (MPa)	Strength Reduction Factor (%)
1	182	639	54
2	179	630	58
3	187	659	59

FRP Recent CSA Standards & Specifications



CSA S6-19

CSA S6 (CHBDC)

- First Edition in 2000 (GFRP as secondary reinforcement)
- Second Edition in 2006 (GFRP as main reinforcement)
- Third Edition in 2010 (FRP-RC beams & slabs, Shear equation, crack-width, Kb,and barrier walls)
- Re-approved in 2014
- Fourth Edition in 2019.

New Clauses in Chapter 16 of CSA S6-19 (in red)

- 16.1 Scope
- 16.2 Definitions
- 16.3 Abbreviations and symbols
- 16.4 Durability
- 16.5 Fibre-reinforced polymers
  - 16.5.1 FRP bars and grids
  - 16.5.2 FRP strengthening systems
  - 16.5.3 FRP tendons
  - 16.5.4 Material properties
  - 16.5.5 Confirmation of the specified tensile strength
  - 16.5.6 Resistance factor
  - 16.5.7 Minimum bend-radius-to-bar-diameter ratio of bent FRP bars

New Clauses in Chapter 16 of CSA S6-19 (in red)

- **16.6 Fibre-reinforced concrete**
- **16.7 Externally restrained deck slabs**
- **16.8 Concrete beams, slabs and columns**
    - 16.8.2.4 Deflections and rotations
    - 16.8.4.2 Development length of FRP bundled bars
    - 16.8.4.3 Development length of FRP bent bar

  – 16.8.5 Development of headed FRP bars and grids
    - 16.8.5.1 Anchorage of headed FRP bar
    - 16.8.5.2 Development length for FRP grids

  – 16.8.7 Design for shear and torsion
  – 16.8.9 Compression components
  – 16.8.10 Cast-in-place deck slabs with FRP stay-in-place structural forms
  – 16.8.11 Strut-and-tie model for deep beams, corbels, and short walls

New Clauses in Chapter 16 of CSA S6-19 (in red)

- 16.9 Stressed wood decks
- 16.10 Barrier walls
  - 16.10.1 FRC barrier wall design details
  - 16.10.2 Barrier wall design details with front and back reinforcement
  - 16.10.3 Test Level 1, 2, 4, and 5 barrier wall design details
  - 16.10.4 Factored punching shear resistance of concrete barrier to transverse traffic
- 16.11 Repair of damaged bridge barrier walls, curbs, and slabs reinforced with FRP bars
- 16.12 Rehabilitation of existing concrete structures with FRP
  - 16.12.4 Retrofit for enhancement of concrete confinement
  - 16.12.5 Retrofit for lap splice clamping

CSA GROUP™

New Clauses in Chapter 16 of CSA S6-19 (in red)

- *Annex A16.1 (informative)740*

Installation of FRP strengthening systems

- *Annex A16.2 (normative)743*

Quality control for FRP strengthening systems

- *Annex A16.3 (informative)*

GFRP composite bridges

CSA GROUP™

Durability/Material properties/New structural materials

16.5.3 Resistance factor (phi factor)

phi factor of GFRP bars increased from 0.55 to 0.65

Rational:

Durability of GFRP bars has been enhanced during the last few years:

1. Better manufacturing process and quality control
2. Better constituents : 1) ECR-Glass versus E-Glass; Most of the GFRP bar manufacturers are using boron-free glass fibres (ECR, commercial name Owens Corning), 2) High-performance resins (advances in polymer chemistry)
3. Durability tests in alkaline solution show high strength retentions without load and under loads (CSA S807): 1) greater than 90-95% (without load), 2) greater than 83-90% (with load).
4. Recently the MTQ took cores for in-service bridges (more than 15 years). No degradation.
5. Durability of GFRP versus durability of concrete? The phi for concrete in the CHBDC is 0.75.

New Clauses in Chapter 16 of CSA S6-19

Maximum Axial Capacity

$$P_0 = \phi_c \alpha_1 f_c' A_g + \phi_f f_f A_f$$

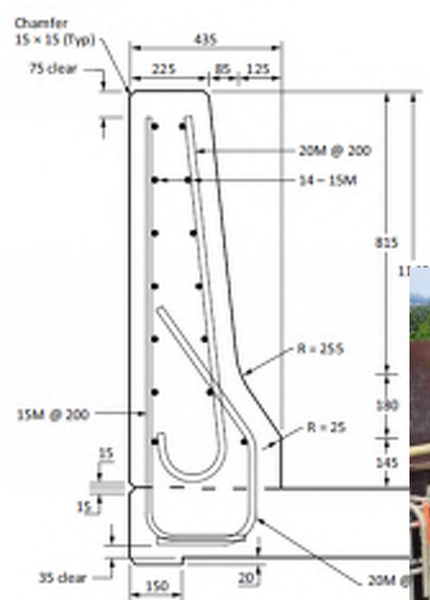
$$f_f = 0.002 E_f$$

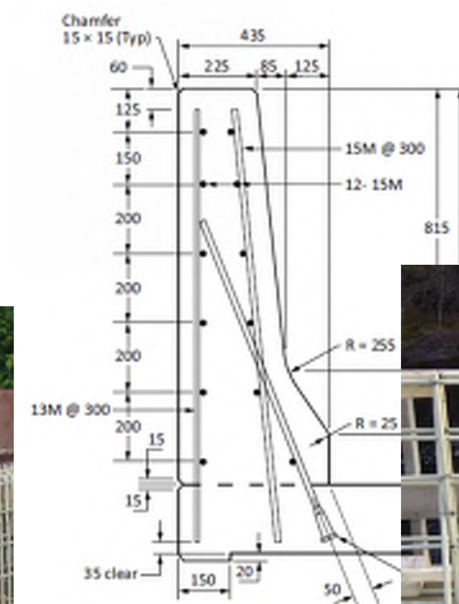
Longitudinal FRP reinforcement may be used in members subjected to combined flexure and axial load. However, the compressive strength of FRP reinforcement shall be limited to a stress corresponding to a strain of 0.002 in the calculation of the factored axial and flexural resistance of reinforced concrete members.

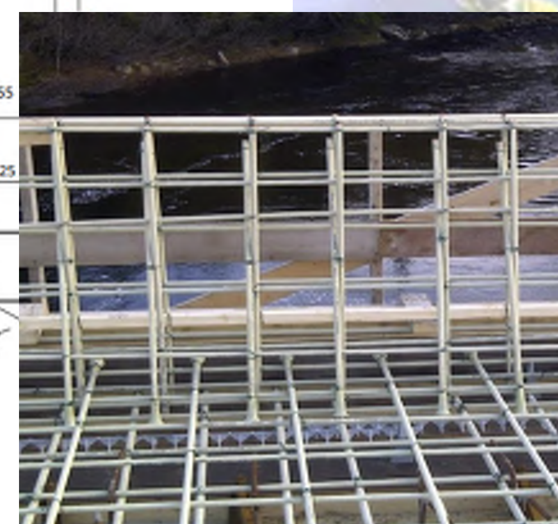
New Clauses in Chapter 16 of CSA S6-19

Barrier walls

The use of headed bars is now allowed for double-face reinforced concrete barriers



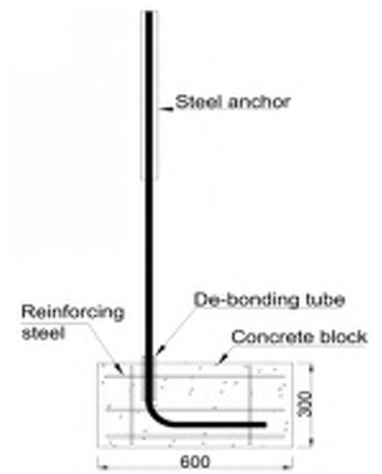




Introduction- FRP Reinforcement in Canadian Codes and Standards: Recent Developments

60 GPa Modulus GFRP Bent Bars Manufactured with a New Process

<u>60 GPa</u> Modulus GFRP Bent Bars Manufactured with a New Process



Modulus of Elasticity: 63 GPa (9 msi)

Tensile Strength of straight portion: <u>1160 MPa (168 ksi)</u>

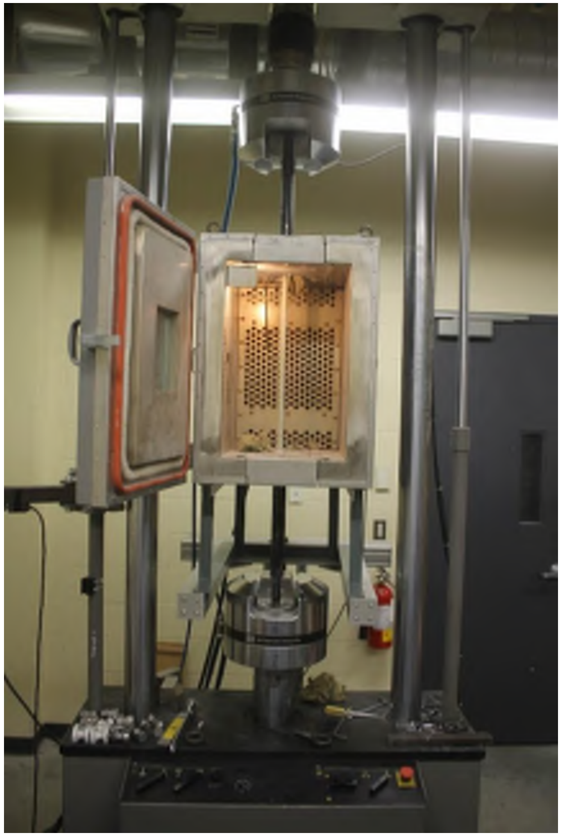
Tensile Strength at bend: <u>700 MPa (100 ksi)</u>

Recent Developments in GFRP Bars

Bendable GFRP bars with <u>thermoplastic resins</u>

Physical, Mechanical, and Durability Characteristics of Newly Developed Thermoplastic GFRP Bars for Reinforcing Concrete Structures

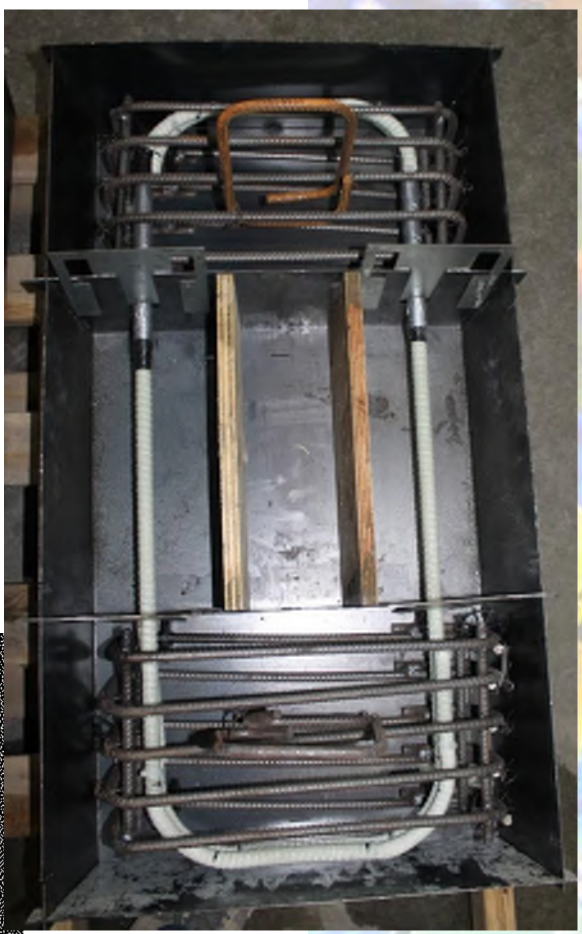


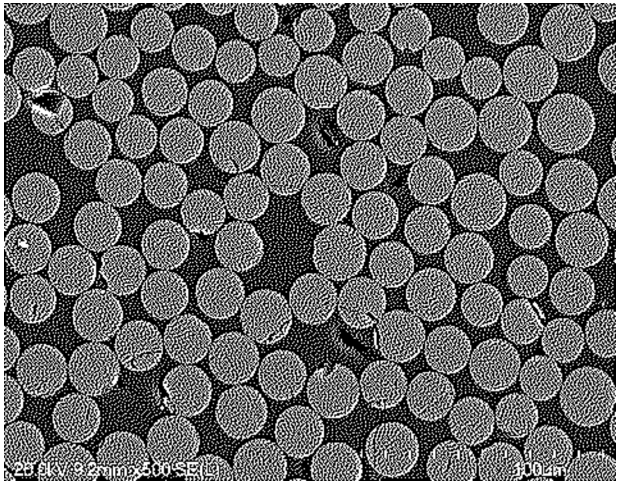



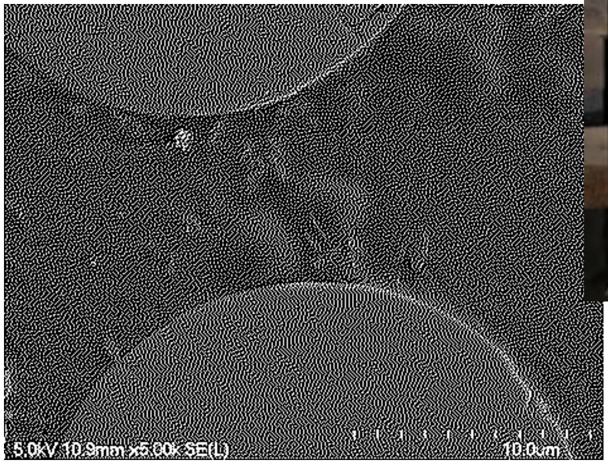

Recent Developments in GFRP

Bendable GFRP bars with thermoplastic resins

Property	Thermoplastic bars		
	#3	#5	#6
Tensile strength (MPa)	1,421	1,062	1,033
Tensile modulus (GPa)	65.4	61.5	62.5
Tensile strain (%)	2.17	1.65	2.14
Transverse shear strength, (MPa)	207	186	-
Interlaminar-shear strength, S_u (MPa)	66.6	46.0	45.1
Bond strength (MPa)	-	27.3	-





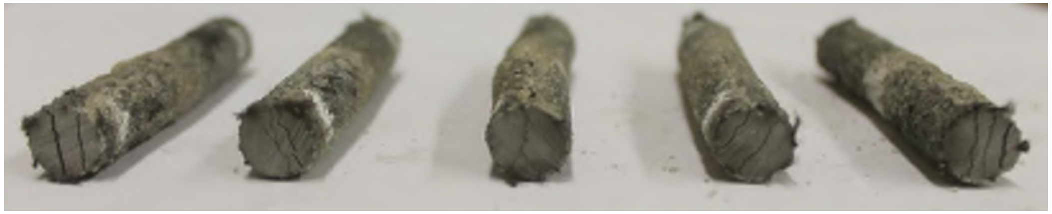


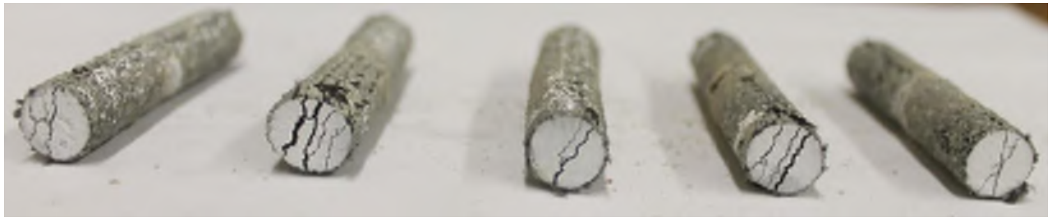
Recent Developments in FRP Bars

<u>Basalt FRP bars</u> with superior resistance to alkali attacks

Property retention after conditioning in alkaline solution for 3 months at 60°C:

Property	Status	Average (MPa)	Retention (%)
Tensile Strength	Reference	1263	**103 %**
	Conditioned	1306	
Tensile Modulus	Reference	51.2	**100 %**
	Conditioned	51.3	
Interlaminar shear strength	Reference	40	**107 %**
	Conditioned	43	





Current Field Applications in Canada using GFRP Bars

- **Bridges** – decks, barriers/parapets, ret walls, sidewalks, app slabs, precast on ped bridges
- **Transit (LRT/BRT)** – bridge structures, platforms, slabs, plinths, track beds, non-conductive components
- **Tunnelling** – soft-eyes; slurry and D walls, caissons, secant piles
- **Buildings** – distribution slabs, warehouse & heated slabs, garage slabs
- **Precast components** – structural and architectural
- **Hydro/substations** – chambers/vaults, duct banks, slabs

B&B FRP Manufacturing, Pultrall, TUF-BAR Canada, SFTec, Pultron, etc.

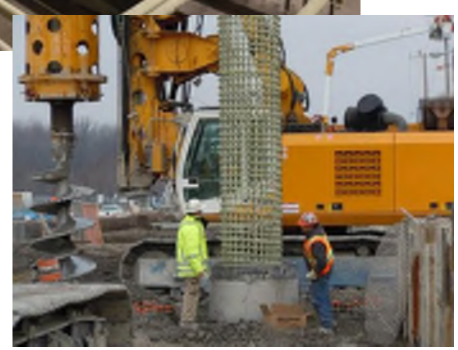
Recent Application of GFRP reinforcement in Infrastructures



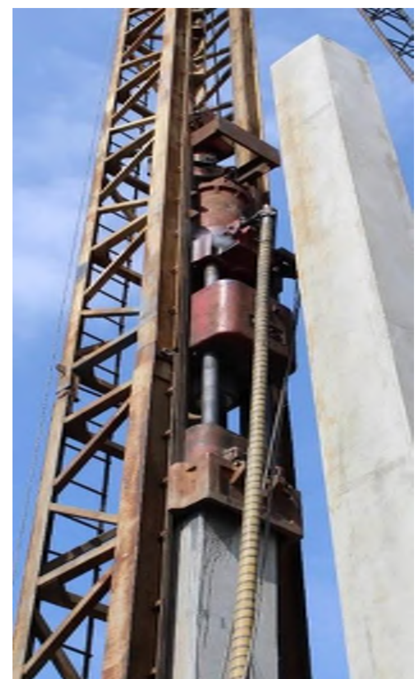




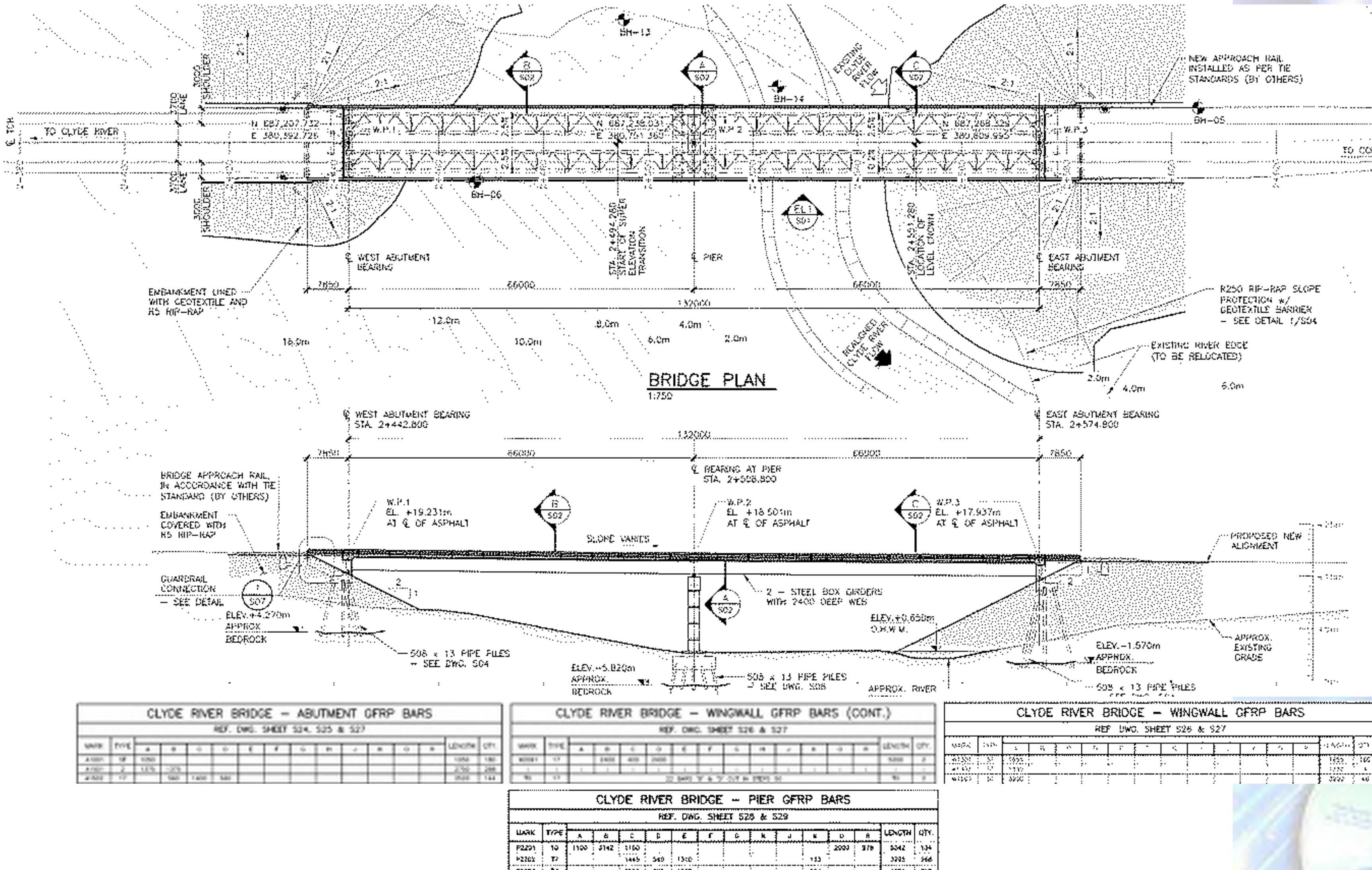




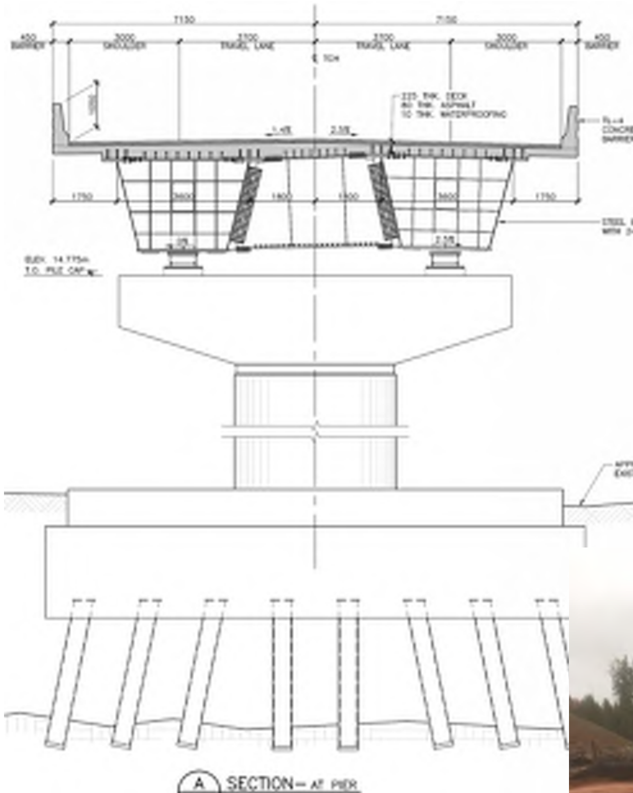

Recent Application of GFRP reinforcement in Infrastructures



Clyde River Bridge – Prince Edward Island, Canada



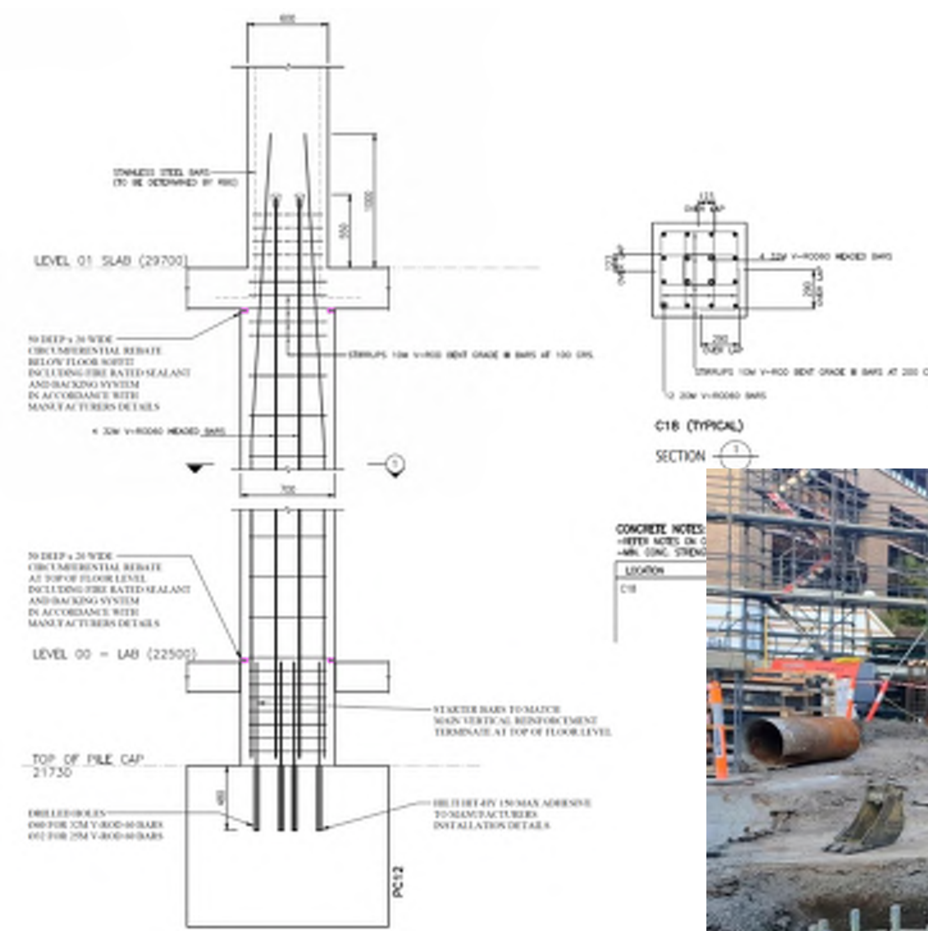
Clyde River Bridge – Prince Edward Island, Canada



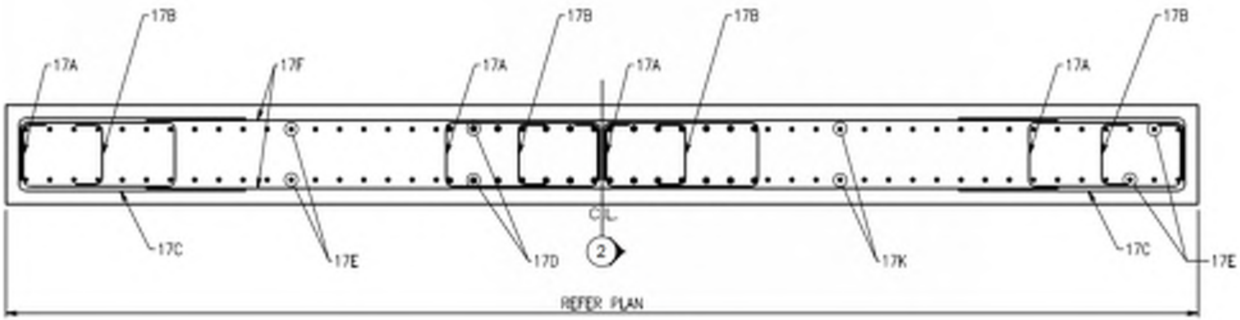
Owner: Province of Prince Edward Island

Contractor: Noye & Noye LTD

LIFE SCIENCES BUILDING – Big portion of the building totally reinforced with GFRP



LIFE SCIENCES BUILDING – Big portion of the building totally reinforced with GFRP



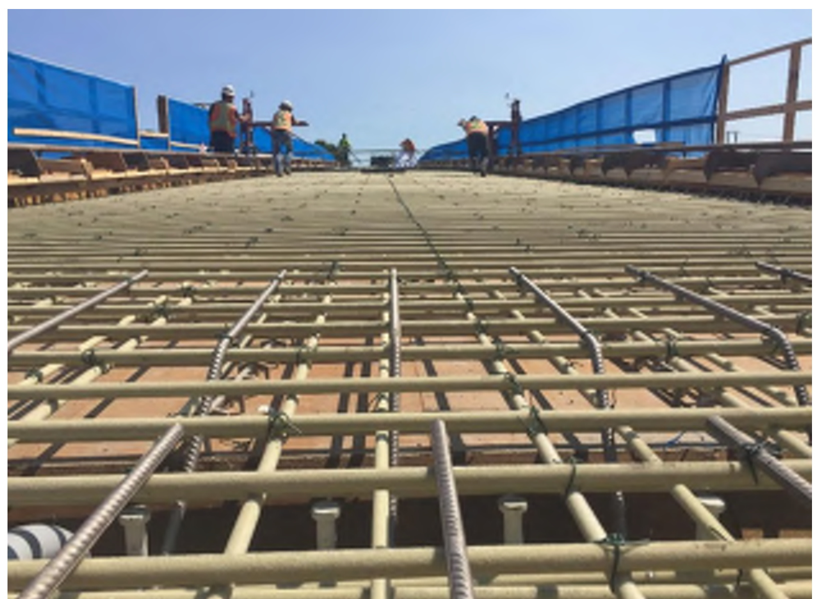
W17 (TYPICAL)

LIFE SCIENCES BUILDING – Big portion of the building totally reinforced with GFRP

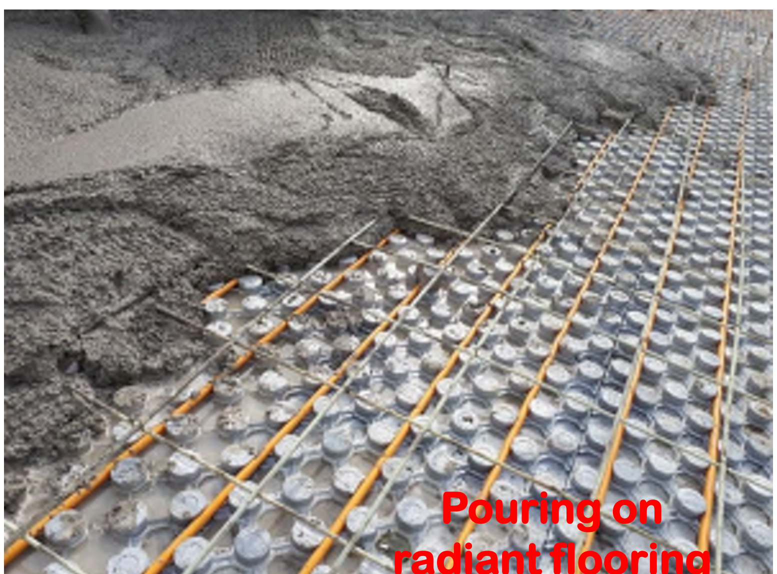
Recent Projects and New Applications

Example of engineering firms that are familiar with the design using FRP bars:

- WSP,
- AECOM,
- Stephenson Engineering,
- RJC,
- Stantec,
- Mott MacDonald,
- ARUP,
- Moses Structural Eng'rs, Entuitive,
- McIntosh Perry,
- Belanger Eng'r Associated,
- NORR,
- Blackwell Structural Engr's,
- IBI Group,
- EXP, CIMA+,
- GM Blue Plan,
- Parsons,
- AMEC Foster Wheeler,
- Brenik Eng'r,
- Dorlan Eng'r,
- Atkins & Van Groll Eng'rs,
- SNC-Lavalin,
- EMS,
- etc.



Recent Projects and New Applications



Recent Projects and New Applications

Underground Enclosures

Recent Projects and New Applications

Transits projects

Concluding Remarks

1. Provisions governing testing and evaluation for certification and quality control/assessment, as well as FRP design provisions, are now in place to regulate the materials specifications and design aspects and guide FRP manufacturers and end-users

2. Application of GFRP bar in different concrete structures in Canada has been proved to be very successful to date

3. The concrete structures reinforced with GFRP bars have a first cost almost the same as concrete structures reinforced with epoxy coated or galvanized steel bars. Stainless steel bars are 2 to 4 times more expensive than GFRP bars.

Concluding Remarks

Current Applications in Bridges & Buildings

Status

- **Very good structural behaviour**
- **Excellent short-term durability (≈ 25 years)**

Thank you for your attention

Contact:

E-mail:brahim.benmokrane@usherbrooke.ca

3-Span GFRP-RC Flat-Slab Bridge and Novel Seawall over Ibis Waterway

Sybille Bayard, PE
E-mail: sbayard@consoreng.com

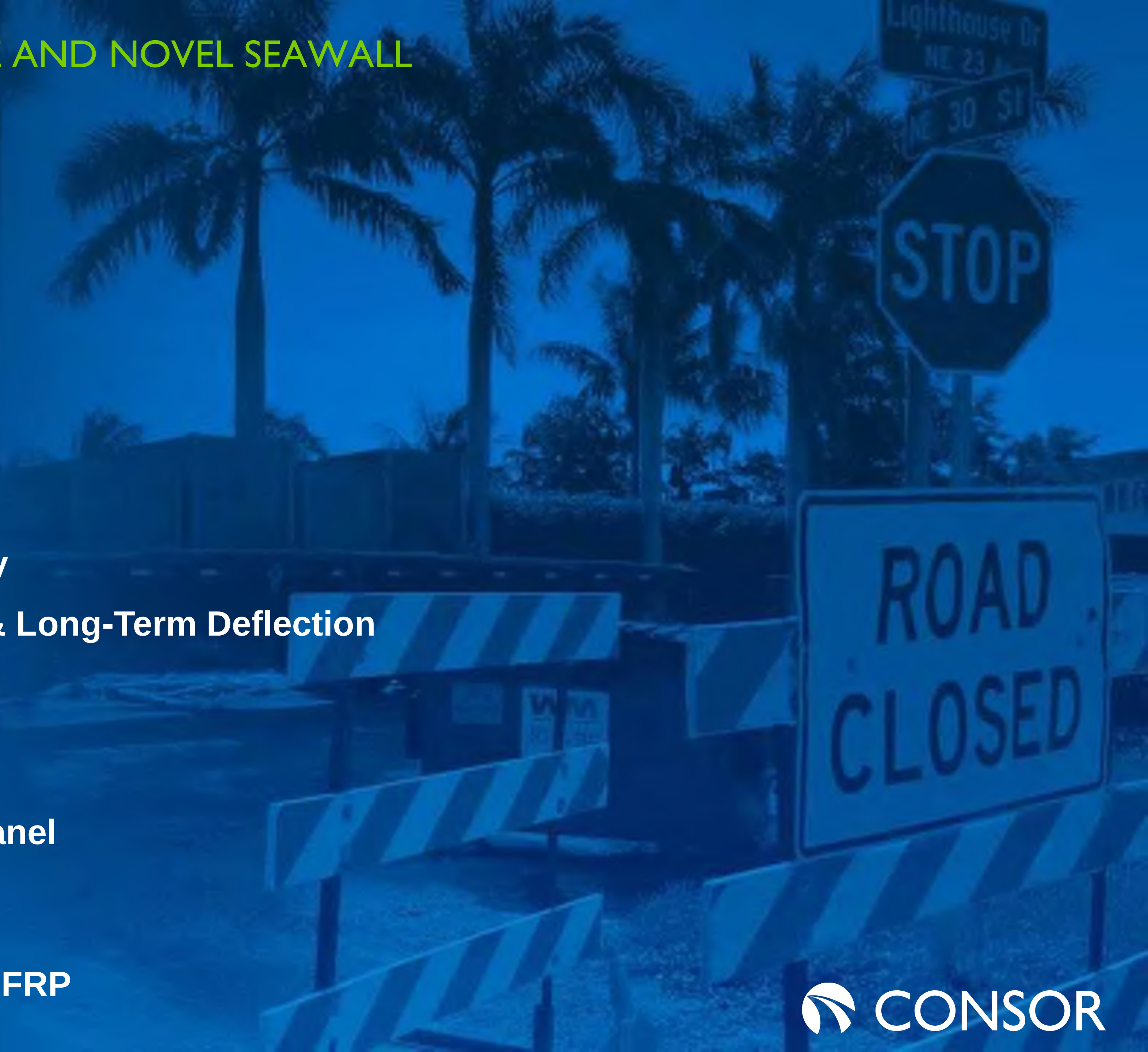
October 27, 2020

CONSOR

3-SPAN GFRP-RC FLAT SLAB BRIDGE AND NOVEL SEAWALL OVER IBIS WATERWAY

Agenda

- Existing Bridge Conditions
- Proposed Bridge Replacement
- Codes and Specifications
- GFRP-RC Continuous Flat Slab
  - Bending Moment Capacity
  - Crack Width Verification & Long-Term Deflection
  - Shear Capacity
- GFRP-RC Bent Cap Design
- GFRP-RC Soldier Wall – Precast Panel
- GFRP Construction Lesson Learns
- Estimated Construction Costs of GFRP



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3-SPAN GFRP-RC FLAT SLAB BRIDGE AND NOVEL SEAWALL OVER IBIS WATERWAY

THANK YOU

- **Steve Nolan, PE – *Florida Department of Transportation***
- **Ramon Otero, PE – *Florida Department of Transportation***
- **Donovan Pessoa, PE – *Florida Department of Transportation***
- **Antonio Nanni, PhD, PE – *University of Miami***
- **Marco Rossini, MS, PhD Candidate – *University of Miami***
- ***Steven R. McNamara – ANZAC Contractors, INC***
- **Yves Amisial, EI – *CONSOR Engineers, LLC***
- **Christopher Howard, PE – *CONSOR Engineers, LLC***
- **Frank Hickson, PE – *CONSOR Engineers, LLC***

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Existing Bridge Conditions

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3-Span GFRP-RC Flat-Slab Bridge and Novel Seawall over Ibis Waterway

Built in 1950

Three-Span Reinforced Concrete T-Beams

Concrete bents supported on 30-in circular concrete piles

Coastal Bridge – extremely aggressive marine environment

Load Restricted Bridge (29 tons)

Age related deterioration evident in substructure/foundation (spalls with some delamination and pile jackets at intermediate bents)

Load Restricted

Proposed Bridge Replacement

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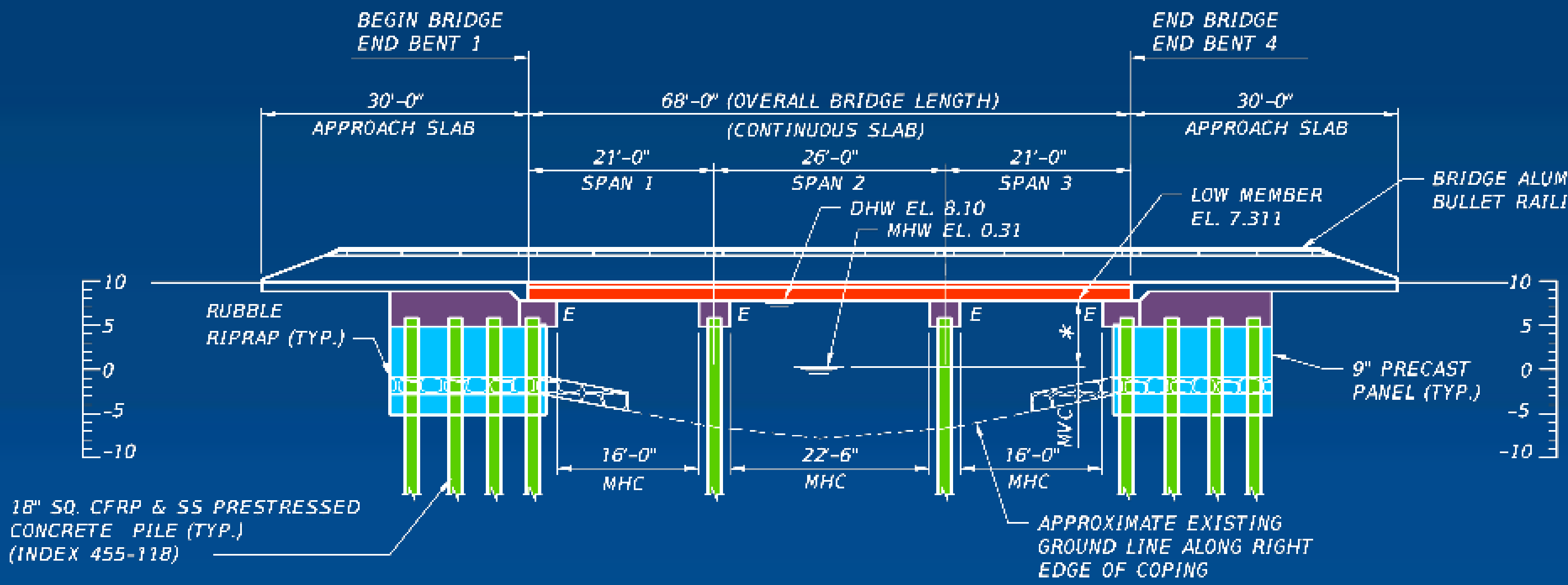

FRP-RC/PCLEGEND

- CIP Flat-slab, 5.5 ksi (1.5-in. cover)
- CIP Caps, 5.5 ksi (3-in. cover)
- Precast Panels, 5.5 ksi (2-in. cover)
- PS Piles, 6 ksi (3-in. cover)

3-span continuous CIP 16-in Flat Slab (21'-26'-21')

- 5.5 KSI Concrete
- Glass Fiber Reinforced Polymer
- 1.5-in cover

CIP Concrete Bents (42-in wide x 36-in deep)

- 5.5 KSI Concrete
- Glass Fiber Reinforced Polymer
- 3-in cover

9-in Precast Concrete Panels at abutments & bulkheads

- 5.5 KSI Concrete
- Glass Fiber Reinforced Polymer
- 2-in cover

CFRP & SS Prestressed Concrete Piles

- FDOT Standard 455-101 & 455-118

Codes and Specifications used in Design

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AASHTO LRFD Bridge Design Specifications for GFRP – Reinforced Concrete Bridge Deck and Traffic Railings, November 2009

FDOT Structures Manual, January 2018

Canadian Highway Bridge Design Code, CSA S6-14, Section 16.8.7

3-SPAN GFRP-RC FLAT SLAB BRIDGE AND NOVEL SEAWALL OVER IBIS WATERWAY

AASHTO LRFD Bridge Design Specifications, 7th Edition

ACI Guide for the Design and Construction of Structural Concrete FRP Bars, ACI 440.1R-15

FDOT Standard Specifications for Road and Bridge Construction, January 2019

Continuous Flat Slab Design

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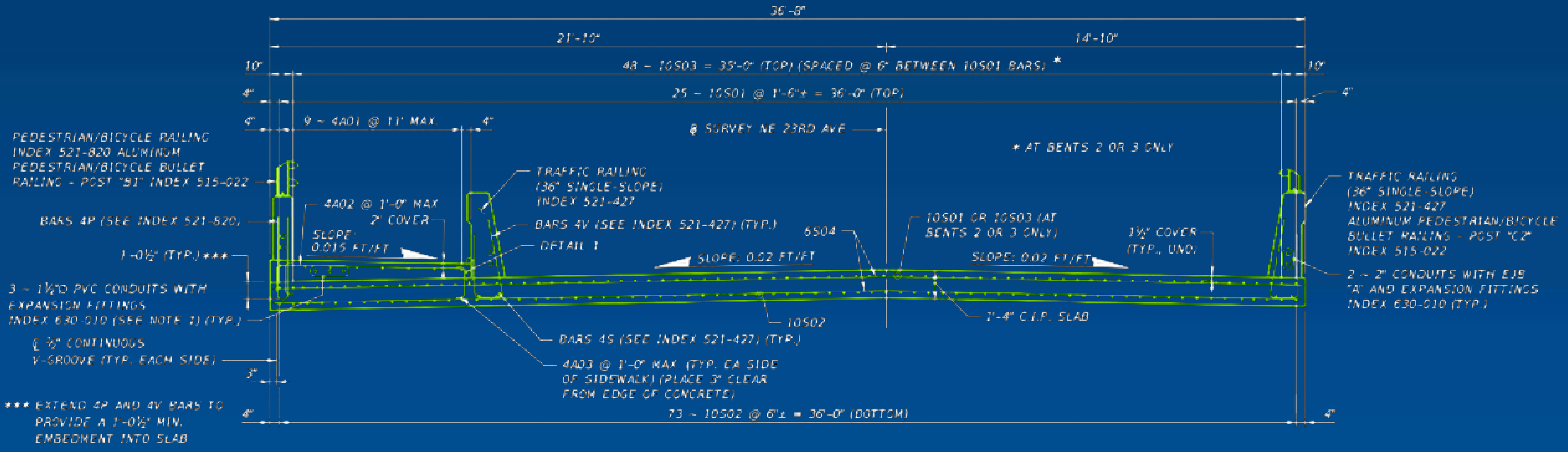

TYPICAL SUPERSTRUCTURE SECTION

COMPARISON CHART BETWEEN CARBON STEEL AND GFRP DESIGN

LOCATION	CARBON STEEL	GFRP
POSITIVE MOMENT (BOTTOM SLAB)	#7 @ 6 in.	#10 @ 6 in.
NEGATIVE MOMENT (TOP SLAB)	#7 @ 6 in.	#10 @ 6 in.
SHEAR REINFORCEMENT	NOT REQUIRED	NOT REQUIRED
LONG TERM DEFLECTION	0.11 in.	0.45 in.

Continuous Flat Slab Design

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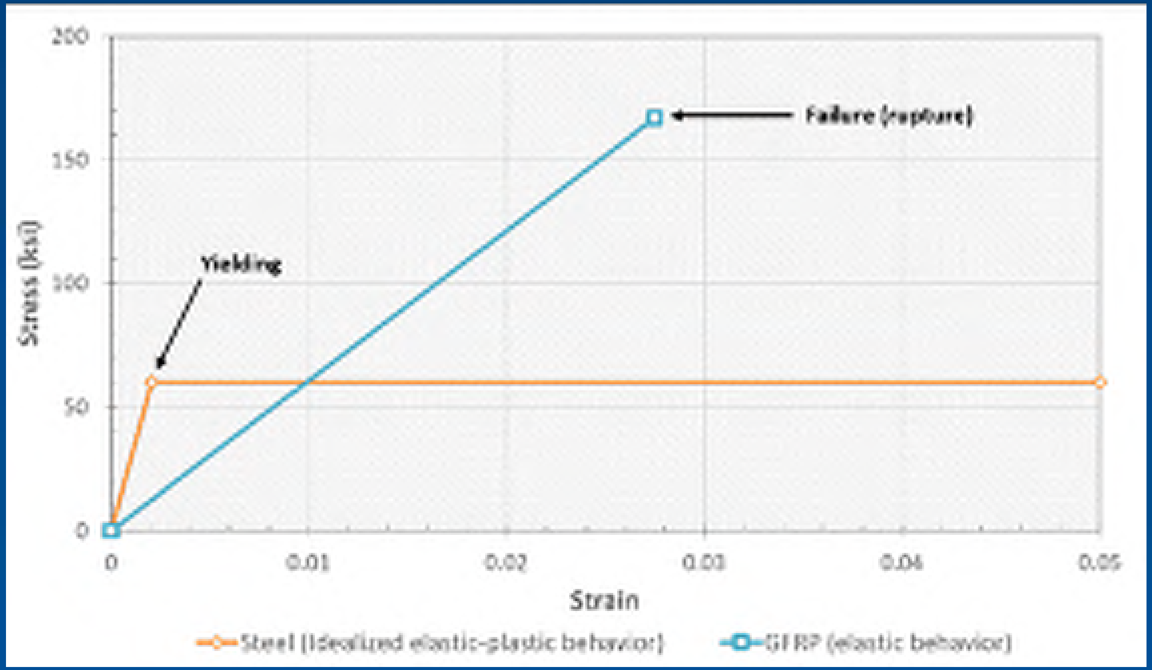
- **Comparing Bending Moment Capacity in the Slab:**

Stress-Strain Curve (Steel vs. GFRP)



GFRP Size and Tensile Loads – FDOT Standard Specifications

Table 3-1
Sizes and Tensile Loads of FRP Reinforcing Bars

Bar Size Designation	Nominal Bar Diameter (in)	Nominal Cross Sectional Area (in^2)	Measured Cross-Sectional Area (in^2) Minimum	Measured Cross-Sectional Area (in^2) Maximum	Minimum Guaranteed Tensile Load (kips) GFRP Bars	Minimum Guaranteed Tensile Load (kips) CFRP Bars
2	0.250	0.049	0.046	0.085	6.1	10.3
3	0.375	0.11	0.104	0.161	13.2	20.9
4	0.500	0.20	0.185	0.263	21.6	33.3
5	0.625	0.31	0.288	0.388	29.1	49.1
6	0.750	0.44	0.415	0.539	40.9	70.7
7	0.875	0.60	0.565	0.713	54.1	-
8	1.000	0.79	0.738	0.913	66.8	-
9	1.128	1.00	0.934	1.137	82.0	-
10	1.270	1.27	1.154	1.385	98.2	-

Tensile strength calculated as:
Guaranteed Tensile Load x C_E
For #10 bars = 54ksi

Continuous Flat Slab Design

➢ **Comparing Bending Moment Capacity in the Slab:**

GFRP

The nominal moment capacity is: [AASHTO GFRP 2009, 2.9.3.2.2-1, 2.9.3.2.2-3]

$$M_{nAASHTO\_1slab} := \left| A_{f1.slab} \cdot f_{f1.slab} \cdot \left(d_{f1.slab} - \frac{a_{f1.slab}}{2} \right) \right. \text{ if } \rho_{f1.slab} \geq \rho_{fb1.slab}$$

Recall the strength reduction factor for slab:

[AASHTO GFRP 2009, 2.12.1.2.1]

$$\phi_{T\_bar1.slab} = 0.55$$

The design flexural strength is computed as:

$$\phi_{T\_bar1.slab} \cdot M_{nAASHTO\_1slab} = 78 \cdot kip \cdot ft$$

Capacity of GFRP- #10@6”

Resistance Factor

Steel

$$\phi = 0.90$$

$$M_{r,pos} = \phi \cdot A_s \cdot f_y \cdot \left[d_s - \frac{1}{2} \cdot \left(\frac{A_s \cdot f_y}{0.85 \cdot f'_{c.slab} \cdot b} \right) \right]$$

$$= 0.9 \times 1.200 \times 60 \times \left[13.563 - \frac{1}{2} \times \left(\frac{1.200 \times 60}{0.85 \times 5.5 \times 12} \right) \right]$$

$$= 69.772 \text{ kip-ft}$$

Capacity of Steel- #7@6”

NOTE: #10@6” would provide a moment capacity of 139 k-ft (steel) vs 78 k-ft (GFRP)

Continuous Flat Slab Design

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- **Crack Width Verification and Long-Term Deflection in the Slab:**

Modulus of Elasticity of Steel = 29,000 ksi

Modulus of Elasticity of GFRP = 6,500 ksi

Crack Width

The crack width under service loads is: [AASHTO GFRP 2009, 2.9.3.4-1]

$$w_{1.slab} := 2\frac{f_{f1.slab}}{E_{f}}\beta_{11.slab}\cdot k_b\cdot\sqrt{d_{c1.slab}^2 + \left(\frac{s_{f.bar1.slab}}{2}\right)^2} = 0.021\cdot in$$

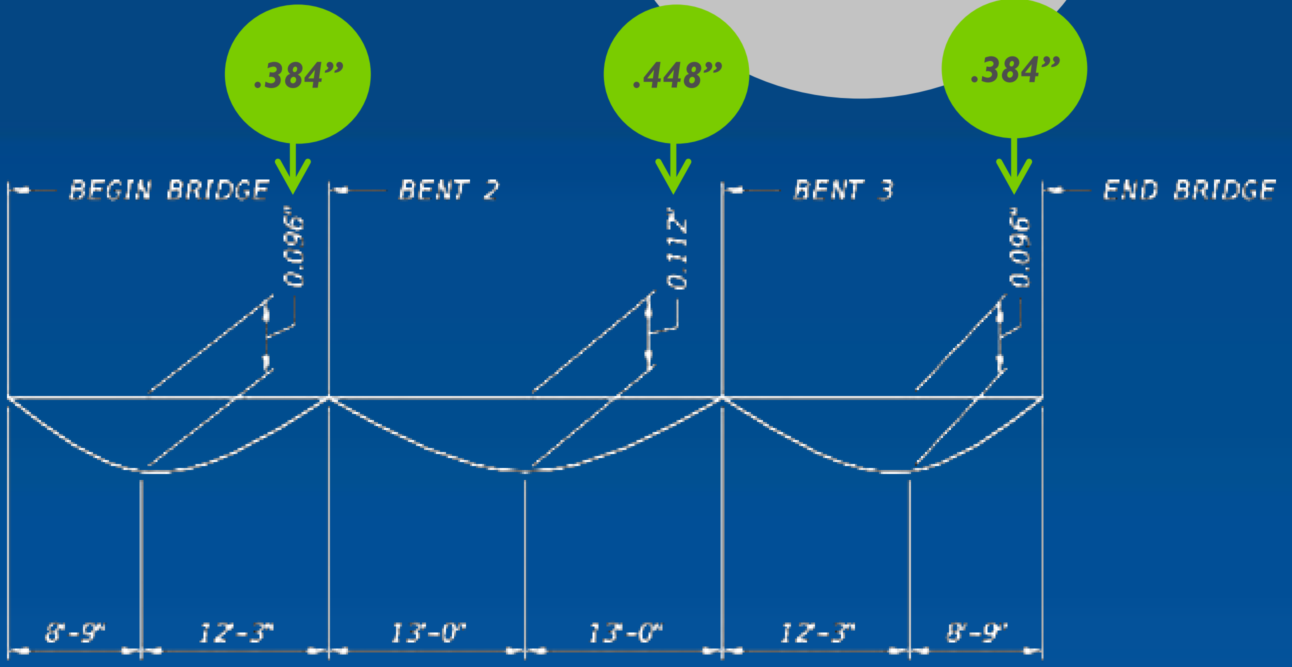
Crack width independent of concrete strength

Crack width limited to 0.028 in.

Deflection

Much larger deflection in GFRP design due to low modulus of elasticity.

Deflection Ratio (GFRP/Steel) = ~4



DEAD LOAD DEFLECTION DIAGRAM

CAMBER THE FORMS TO COMPENSATE FOR THE COMBINED EFFECT OF THE FORMS AND THE LONG TERM DEAD LOAD DEFLECTION OF THE SLAB.

Continuous Flat Slab Design

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- **Shear Capacity in the Slab:**

Initial design prior to application of the Canadian Code

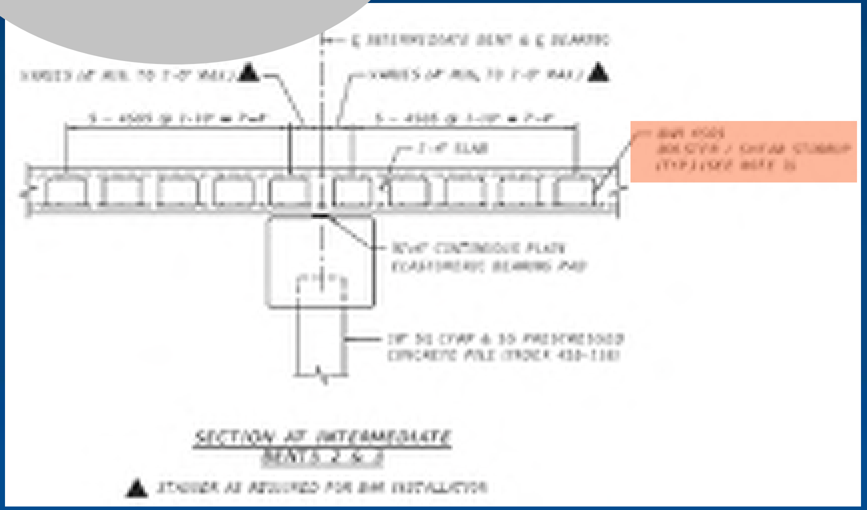
Shear Capacity per AASHTO GFRP 2009

$c_{1.slab} := \frac{e_{f1.slab}}{\beta_{1.super}} = 4.1\ in$ neutral axis depth at support

$V_{c1.slab} := 0.16\sqrt{f'_{c.super}\ ksi}\ b_{slab}\ c_{1.slab} = 16.8\ kip$ [AASHTO GFRP 2009, 2.10.3.2.1-1]

Resistance factor ϕ_v for shear is 0.75 [AASHTO GFRP 2009, 2.7.4.2]

$\phi_v V_{c1.slab} = 12.6\ kip$



Shear Capacity almost doubled assuming the Canadian Code

$f_{cr.slab} := 0.4\sqrt{\frac{f'_{c.super}}{ksi}}\ ksi = 0.9\ ksi$ Cracking Strength of Concrete

$V_{c1.slab} := 2.5 \cdot 3 f_{cr.slab}\ b_{slab}\ d_v = 32.9\ kip$ [ACI Structural Journal, equation (4)]

$V_{c2.slab} := 2.5 \cdot 3 f_{cr.slab}\ b_{slab}\ d_v = 32.9\ kip$ [ACI Structural Journal, equation (4)]

Resistance factor ϕ_v for shear is 0.75 [AASHTO GFRP 2009, 2.7.4.2]

$\phi_v V_{c1.slab} = 24.7\ kip$

Canadian Highway Bridge Design Code—CSA S6-06[15] specifies an algorithm for V_c that is based on the MCFT[13] and is herein given in the following corrected[40,41] form

$$V_n = 2.5\beta f_{cr} b_w d_v$$

$$\beta = \left(\frac{0.4}{1+1500\varepsilon_x}\right)\left(\frac{1300}{1000+s_{ze}}\right) \quad (4)$$

Shear Capacity equation per the Canadian Highway Bridge Design Code

End Bent/Intermediate Bent Cap

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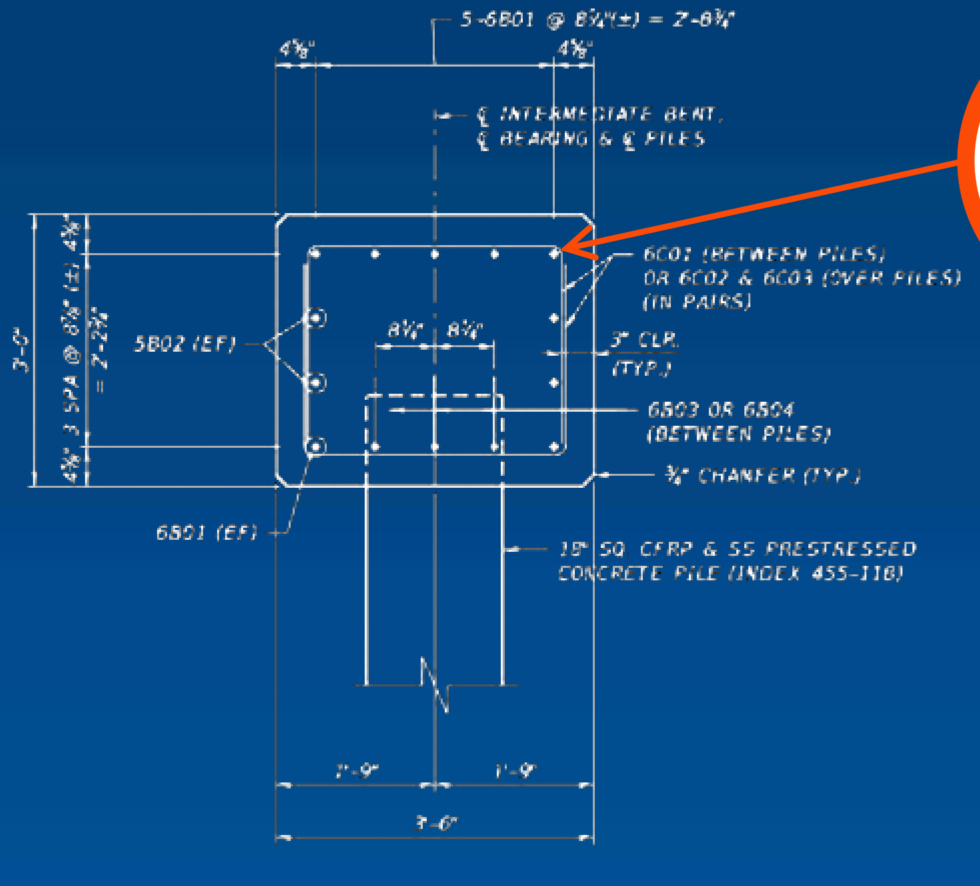
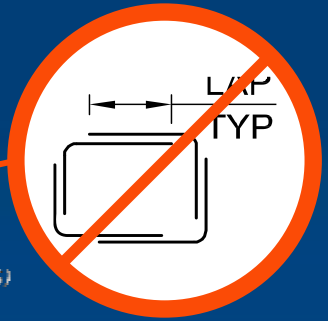
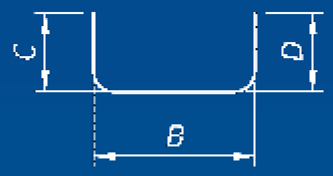


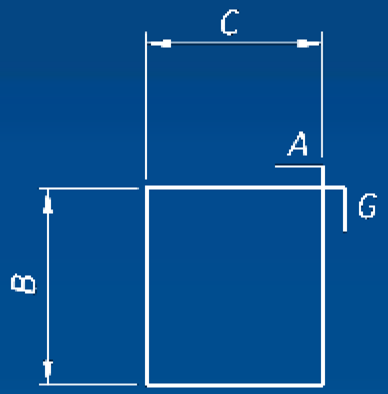
SECTION A-A



Specify pairs of U-bars rather than closed stirrups



TYPE 11



TYPE 4

GFRP bar layout at Intermediate bent 2

COMPARISON CHART BETWEEN CARBON STEEL AND GFRP DESIGN

LOCATION	CARBON STEEL	GFRP
POSITIVE MOMENT (BOTTOM REINFORCEMENT)	4#6	5#6
NEGATIVE MOMENT (TOP REINFORCEMENT)	4#6	5#6
SHEAR REINFORCEMENT (STIRRUPS)	#5 @ 11 in.	#6 @ 8 in.

Soldier Pile Walls – Precast panels

- **Fatigue and Creep Rupture Limit**

  SERVICE = 1.0EH + 1.0WA + 0.2LS

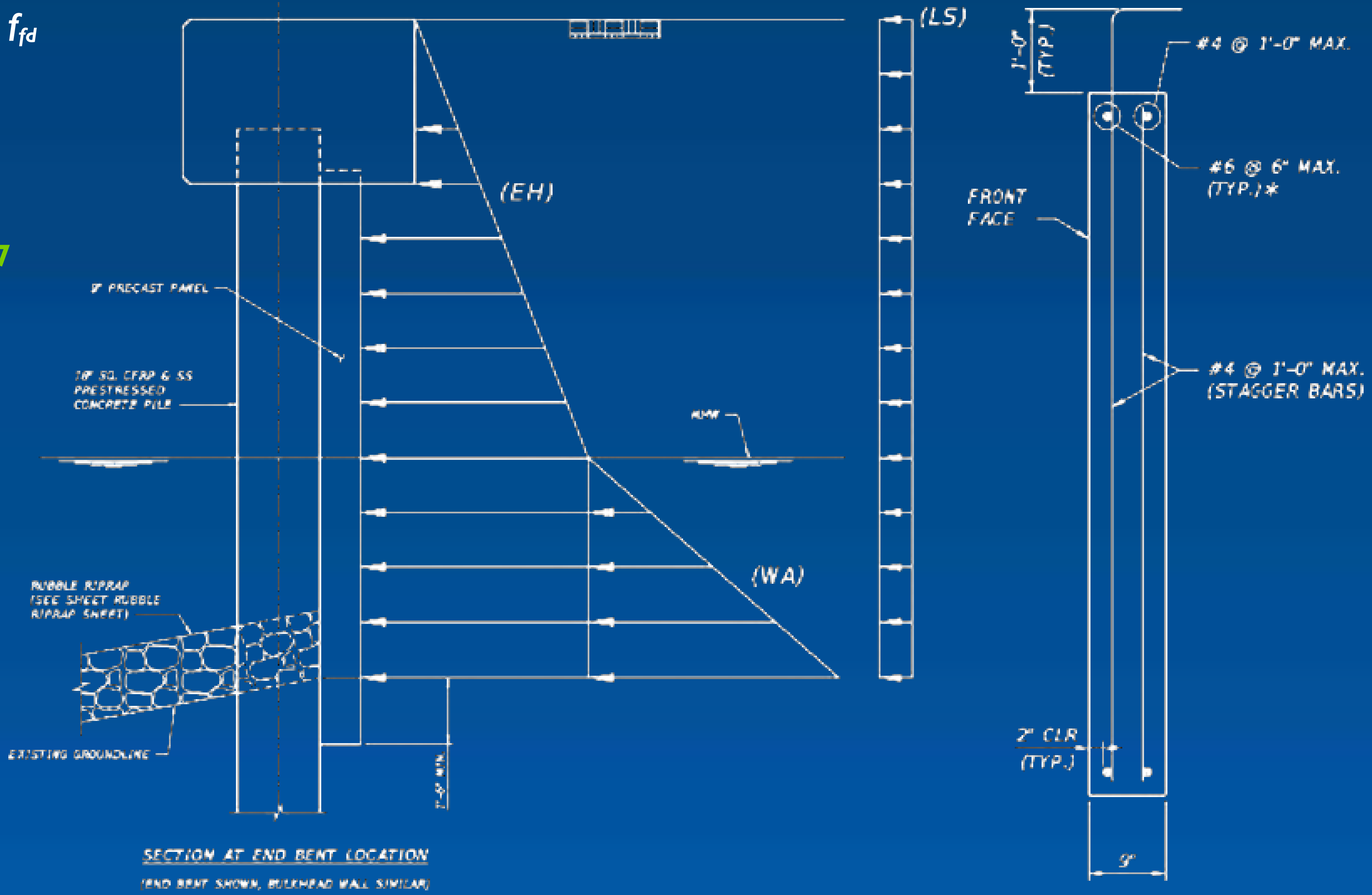
  Maximum sustained tensile stress: $f_{fs} \leq C_C \times f_{fd}$

  Where:

  C_C **is the Creep rupture reduction factor, equal to 0.3**

  f_{fd} **is the guaranteed tensile strength** $\times$ **environment reduction factor, equal to 0.7**

Precast panels installed at End Bent 4



GFRP Construction Lesson Learns:

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Pile Driving

Utility Conflict - Overhead Power Lines

Pile Location Verification

Underground Force Main and Water Mains

GFRP Construction Lesson Learns:

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Transportation, Delivery & Handling

Transportation and Delivery

Damaged Panels during construction

GFRP Construction Lesson Learns:

The light weight of GFRP allows for much easier installation, less demand on workers, and much more time efficient

Considerations in Construction Time and Schedule:

- No Field Bending – No room for deviation
- GFRP bars not readily available
- Requires 6-8 weeks for manufacturing
- Not available locally – account for transportation time and cost

Estimated Construction Costs of GFRP

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$1.68 (winning bid)

GFRP AS-BID CONSTRUCTION COSTS				
Pay Item Description	Unit	Quantity	Unit Price	Total Price
Fiber Reinforced Polymer Bars, #5 Bar	LF	2,804	$0.99	$2,775.96
Fiber Reinforced Polymer Bars, #6 Bar	LF	11,110	$1.68	$18,664.80
Fiber Reinforced Polymer Bars, #8 Bar	LF	2,081	$2.29	$4,765.49
Fiber Reinforced Polymer Bars, #10 Bar	LF	8,610	$4.37	$37,625.70
TOTAL ESTIMATED COSTS OF GFRP (Slab, Bents, & bulkheads)				$63,831.95

$1.16 (traffic railings)

REINFORCING STEEL ESTIMATED CONSTRUCTION COSTS				
Pay Item Description	Unit	Quantity	Unit Price	Total Price
Reinforcing Steel - Superstructure	LB	27,605	$1.00	$27,605.00
Reinforcing Steel - Substructure	LB	8,579	$1.00	$8,579.00
Reinforcing Steel - Bulkhead	LB	6,005	$1.00	$6,005.30
TOTAL ESTIMATED COSTS OF REINFORCING STEEL (Slab, Bents, & bulkheads)				$42,189.30

Typically $2.00

Cost of GFRP

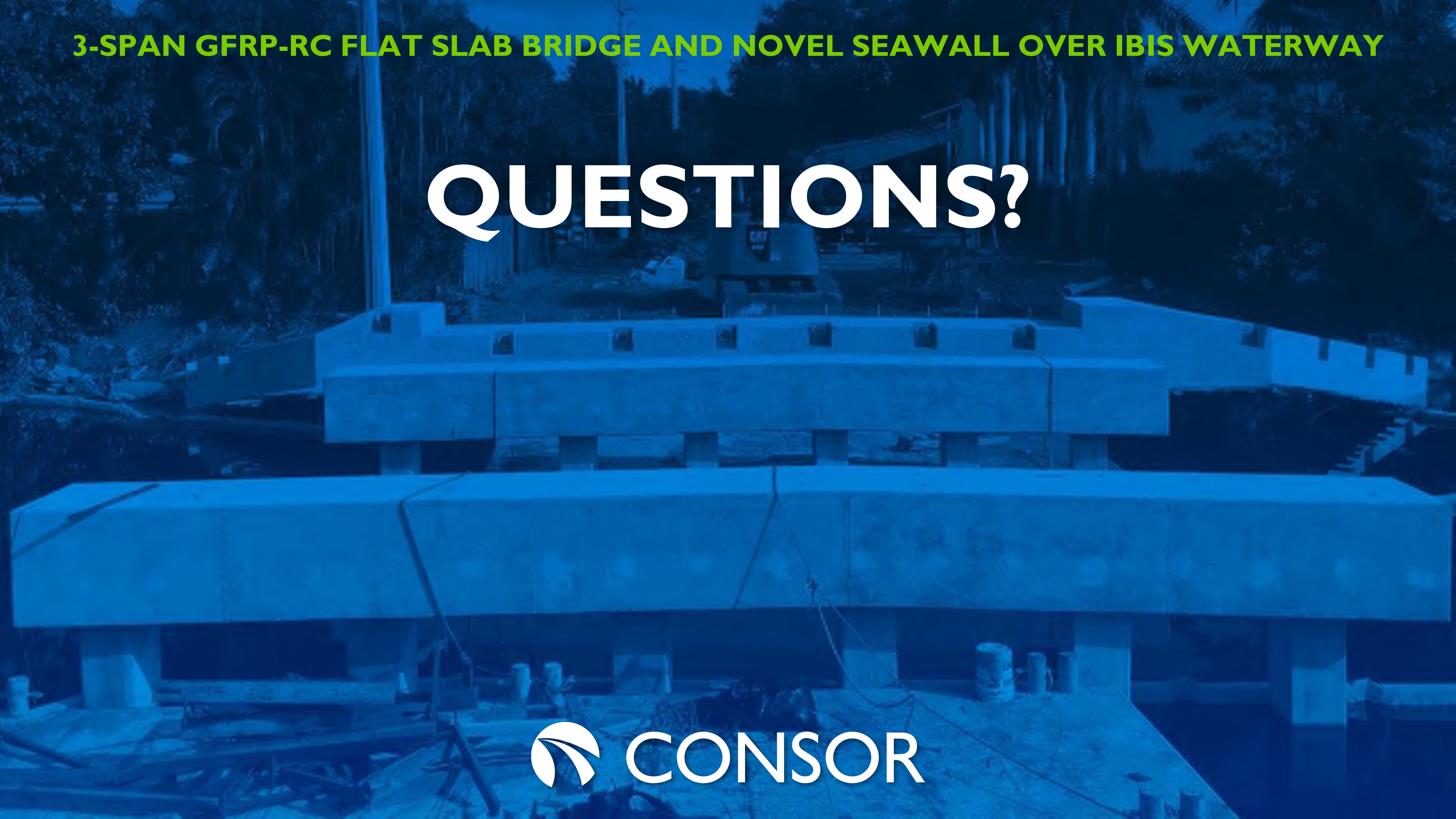
NOTE:

50% increase in the cost of GFRP. However this contributes only a 1% increase in the overall cost of the bridge

OTHER BENEFITS

- ***Durability (100+ yrs)***
- ***No corrosion-related maintenance***
- ***Lightweight (Construction workmanship & time-efficiency)***

Cost of Steel


3-SPAN GFRP-RC FLAT SLAB BRIDGE AND NOVEL SEAWALL OVER IBIS WATERWAY
QUESTIONS?
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2020 ACI CONCRETE CONVENTION
- A VIRTUAL EXPERIENCE -

FIELD APPLICATIONS OF NON-CONVENTIONAL REINFORCING AND STRENGTHENING METHODS FOR BRIDGES AND STRUCTURES

5,000 Feet (1.6 km) GFRP-RC Seawall/Bulkhead protects State-Highway A1A along Flagler Beach, Florida - USA

SESSION 37: PART 2 of 3 - October 28, 2020 (11:02 Hours)

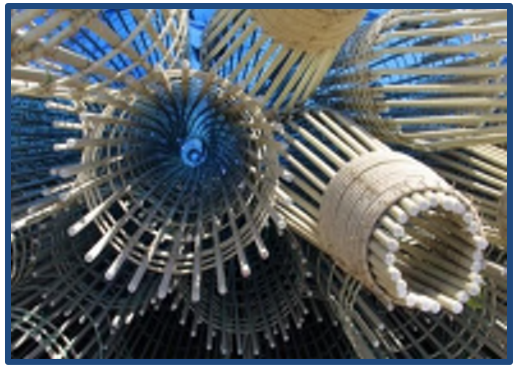
THE WORLD'S GATHERING PLACE FOR ADVANCING CONCRETE

aci VIRTUAL CONCRETE CONVENTION

5,000 Feet (1.6 km) GFRP-RC Seawall/Bulkhead protects State-Highway A1A along Flagler Beach, Florida - USA

UNIVERSITY OF MIAMI
Advanced Structures and Materials Laboratory

Christian C. Steputat, P.E., LEED AP BD+C
Ph.D. Candidate



THE WORLD'S GATHERING PLACE FOR ADVANCING CONCRETE

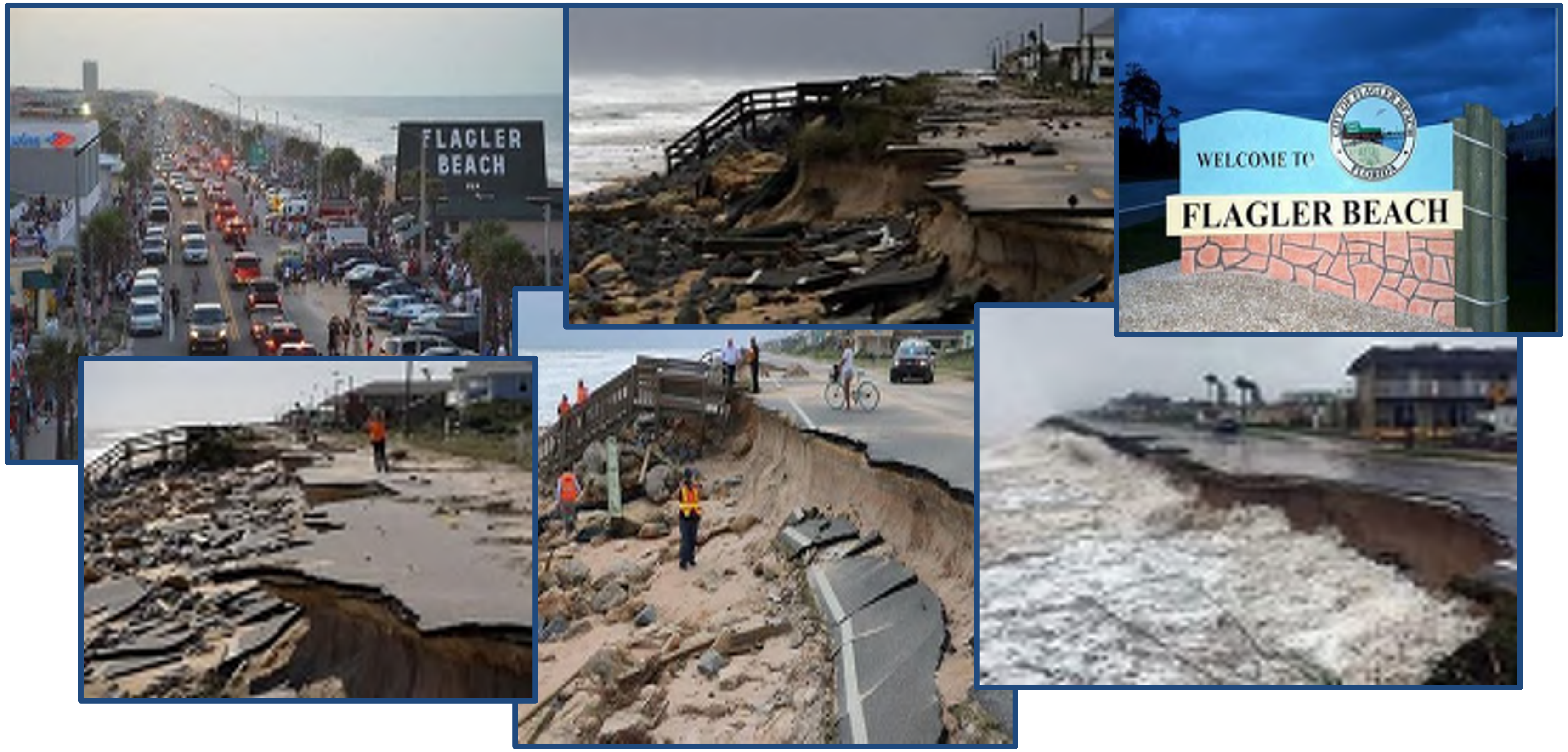
aci VIRTUAL CONCRETE CONVENTION

Hurricane Matthew in 2016 impacted Flagler Beach, FL

Remains left in the wake of Hurricane Matthew in 2016. Destructive forces at work resulted in the "wash-out " and destruction of the essential ***State Road A1A****, which is an Evacuation Route and is* ***Critical to the Infrastructure****.*

- Severe corrosion damage of existing steel sheet-pile bulkheads and *extensive erosion damage of adjacent sand dune systems.*

- Implementation of intervention, to *avoid future collapse-type of damage* to SR-A1A, along Flagler Beach.



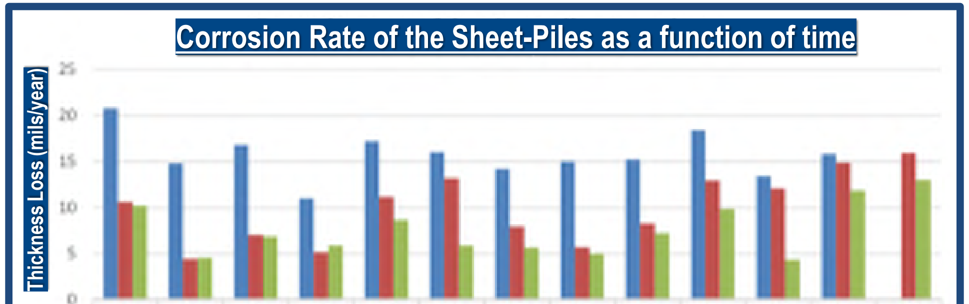
The most recent damage from Hurricane Matthew in 2016, resulted in severe damage and undermining of almost one mile of the State Highway (SR-A1A).

STEEL SHEET-PILE WALL THICKNESS EVALUATIONS (BY OTHERS)

State Road A1A (SR-A1A), Flagler Beach, Florida - Seawall Summary of Findings and Results

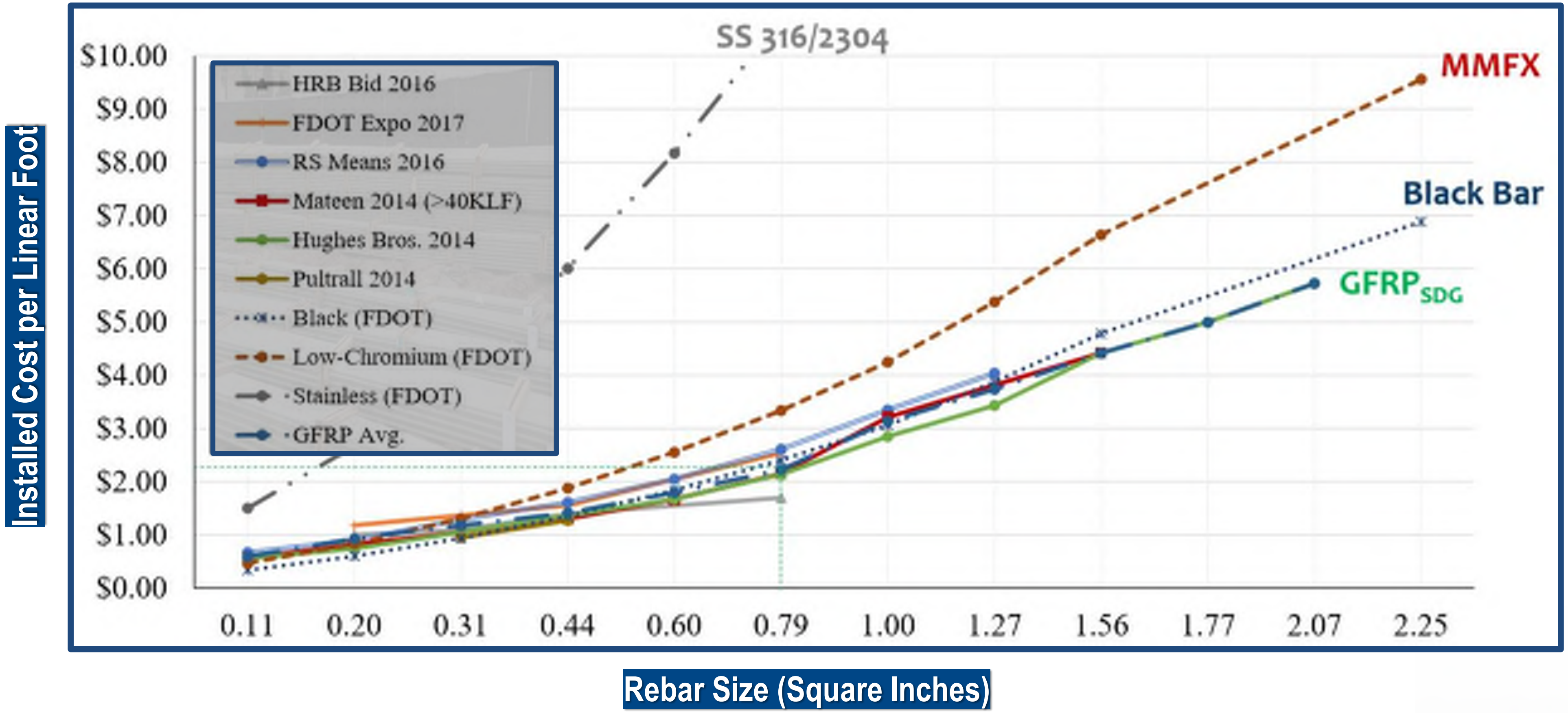
Wall-Thickness Evaluation of SR-A1A Sheet Pile Retaining Wall at Flagler Beach (January 8, 2016)

- *"…If the corrosion progresses at the current rate, in the next 3 years many piles will start losing the sacrificial steel and no piles will have any sacrificial steel remaining in the next 7 years."*
- *Average section-loss up to 13 mils/year > 2 times SDG 3.1*



	3	6	9	12	15	18	21	24	27	30	33	36	39
2011	20.8	14.8	16.8	11	17.2	16	14.2	15	15.2	18.4	13.4	15.8	0
2015	10.61	4.43	7.03	5.16	11.18	13.18	7.95	5.69	8.27	12.97	12.08	14.87	15.92
2016	10.22	4.55	6.88	5.88	8.66	5.88	5.66	5	7.22	9.88	4.33	11.88	13

STEEL-REINFORCING vs. GFRP-REBAR Cost Comparison (Published and FDOT Bid-Estimates)



STATE ROAD A1A (SR-A1A), FLAGLER BEACH, FLORIDA - ALTERNATIVES SELECTION

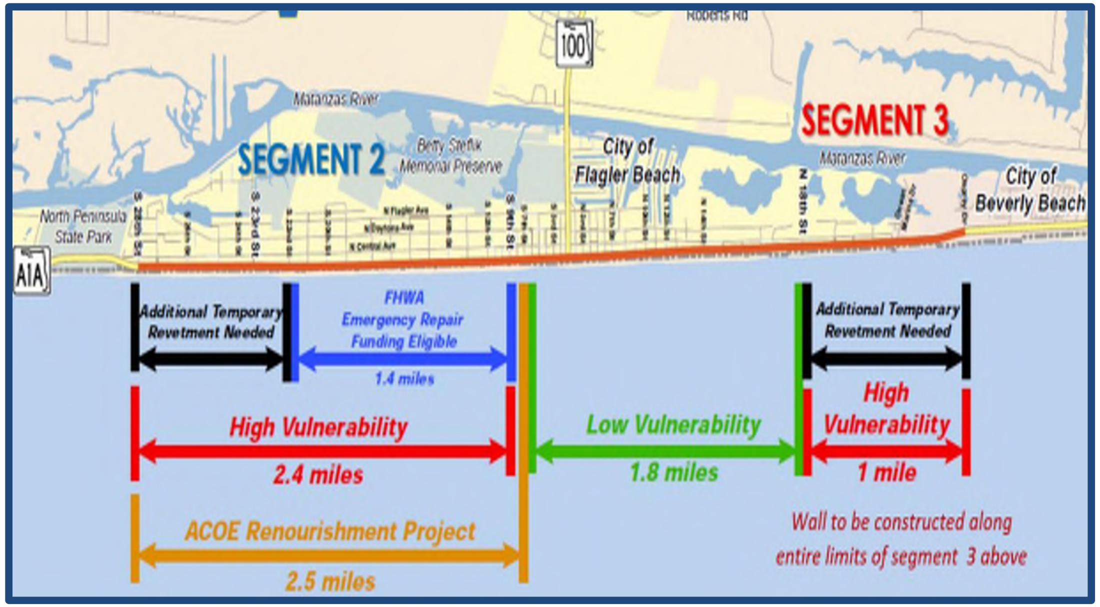
Alt. No.	Seawall/Bulkhead-Type Description	Wall Cost per Linear Foot	Weighted Scores				Total Score	Final Rank
			Cost 50%	RUI 25%	Const. 5%	Maint. 20%		
1	36 Inch Diameter Secant-Pile Wall (Steel-Rebars)	$ 2,123.16	250	86	25	50	411	2
2	36 Inch Diameter Secant-Pile Wall (GFRP-Bars)	$2,308.00	230	86	25	100	441	1
3	Anchored Steel Sheet-Pile Wall (Sections)	$2,146.63	247	125	8	25	406	3
4	Double Cantilever Sheet-Pile Wall (Sections)	$2,790.81	190	94	13	33	330	4

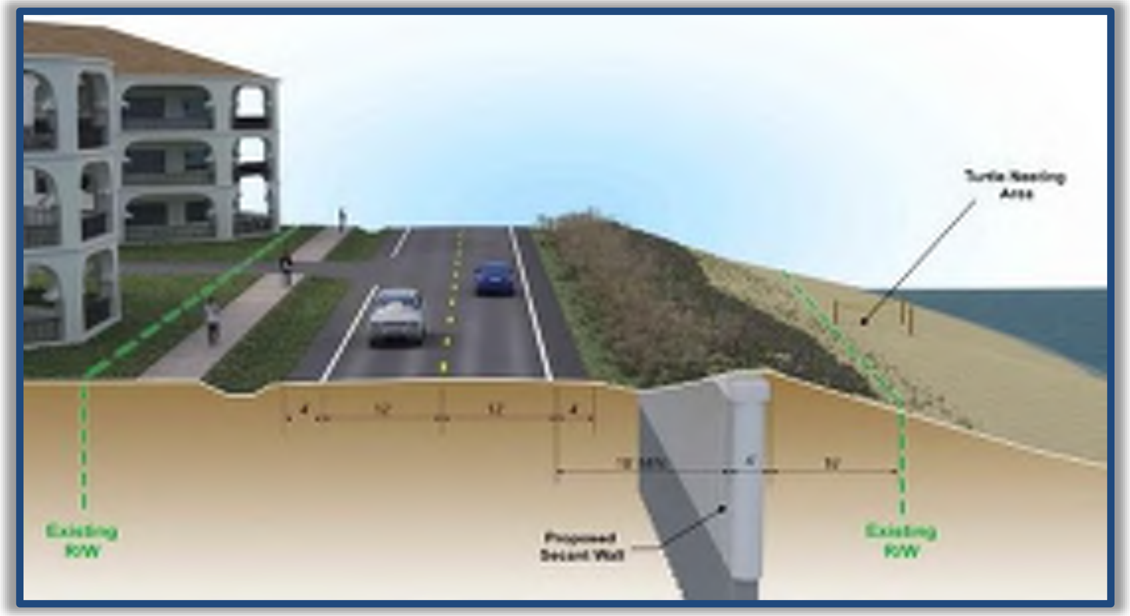
Note: State Road A1A (SR-A1A) Segment-3 Seawall/Bulkhead Feasibility-Study Cost Comparison (Report Update completed in 2017). Data provided, as published by FDOT, with Alternatives Selection Process shown. The GFRP Alternative 2 was selected.

Table 1: State Road A1A (SR-A1A) Seawall/Bulkhead-Type Alternatives considered and ranked for construction to fortify the Evacuation-Route (Zone-A) and Dune-System

This ***Alternative-2*** was selected, due to the *corrosion-resistant GFRP's reinforcing*, relative "ease" of construction (the site conditions have Coquina Rock, i.e. difficult to drive sheet-pile sheeting), less equipment requirements, relative "fast" speed of construction installation, since no pre-drilling is required, and less community impact, due to less vibration and noise.

STATE ROAD A1A (SR-A1A), FLAGLER BEACH, FLORIDA - VULNERABILITY LIMITS

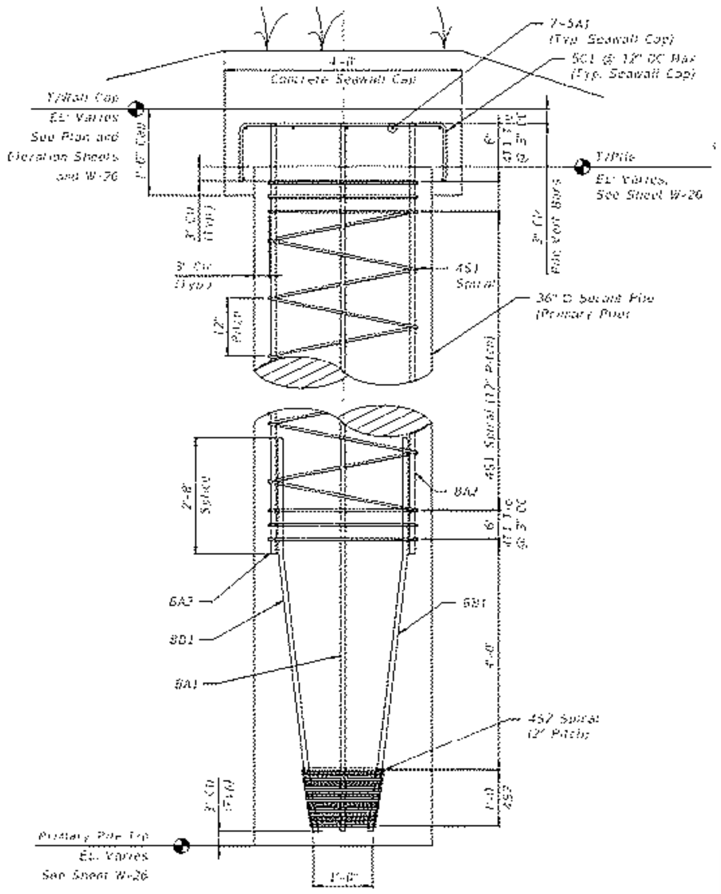




The most recent damage from Hurricane Matthew in 2016, resulted in severe damage and <u>undermining of almost one mile of the State Highway A1A</u>. The <u>Recovery-Phase</u> includes the building of a <u>Secant-Pile Seawall/Bulkhead</u> along the <u>High Vulnerability Limits in Segment-3</u>, with additional temporary revetment needed.

Utilization of GFRP bars for reinforcing

- *4920' length of Secant Pile seawall with GFRP reinforcement long-term durability and additional corrosion protection.*
- *First FDOT project with greater than one million linear feet of GFRP reinforcing bar.*
- *Utilization of GFRP bars in lieu of traditional Grade-60 steel rebar in the secant pile which are tipped in a high chloride content sand and water table, and top periodically exposed to salt spray when exposed.*



PRIMARY PILE & CAP SECTION (SHOWN)
INTERMEDIATE PILE WITH SINGLE CENTER BAR ONLY

GFRP Secant-Pile Cage-Assemblies Documented

- *Note the layout of the **GFRP** bars and (toe-ends)*
- *One tension-type **GFRP** bar in the center of the Secant-Piles will be installed in the field ("wet-insert")*
- *Alternate piles will only receive one center **GFRP** bar*
- ***GFRP-Ties** are not Steel Wire-Ties (see Pictures)*
- ***GFRP Cage-Assembly** was "quick" and "lightweight"*

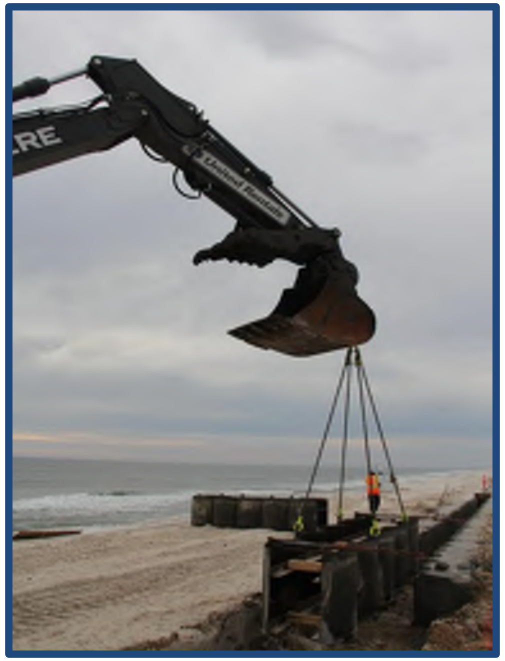
The ***GFRP bars*** and ***Cementitious Materials with Grout Fluidifier*** are expected to significantly reduce the maintenance and repair costs over the life cycle of the seawall/bulkhead project and were instrumental in the rapid installation time of the ***GFRP-Cages*** due to the *GFRP bars light-weight and fluidity* ("mid-range" grout fluidifier) of the concrete-grout. ***Product performance testing*** indicates a **70%** improvement of water retentivity, per **ASTM C-941**, **0%** bleeding and **2% to 3%** expansion, per **ASTM C-940** and a normal setting time, per **ASTM C-953**. The ***GFRP Laboratory Testing Results Summary*** for Lot-1, Lot-2 and Lot-3 are shown below:

Test Prefix	Standard Test Method	Laboratory Test Descriptions	Laboratory Test Results				FDOT Section 932-3, Table 3-4 Requirements
			Lot 1	Lot 2	Lot 3	Mean	
DSC	ASTM E2160	Degree of Cure, %	98	100	100	99.3	≥ 95
	ASTM D3418	Glass Transition Temperature, °F	225	275	256	252	≥ 212
FC	ASTM D2584	Fiber Content (by weight), g	84	84	84	84	≥ 70
MAS	ASTM D570	Moisture Absorption (short term), %	0.17	0.18	0.12	0.16	≤ 0.25
MXA	ASTM D792	Measured Cross-Sectional Area for No. 8 bar, $in.^2$	0.818	0.825	0.803	0.815	> 0.738 < 0.913
TNS	ASTM D7205/D7205M	Guaranteed Tensile Load, kip	111.4	93.6	104.3	103.1	> 66.8
		Tensile Modulus of Elasticity, ksi	8280	7980	7600	7950	≥ 6500
Note: °C = (°F − 32) / 1.8 ; 1 g = 0.04 oz. ; 1 $in.^2$ = 645 mm^2 ; 1 kip = 4.4 kN ; 1 ksi = 6.9 MPa							

Table 2: GFRP Bars - Laboratory Testing Results Summary for Field-Sampled and Laboratory Tested Lot 1, 2 and 3

Laboratory Testing compliance of GFRP rebars, with respect to FDOT Specifications, was demonstrated and *Laboratory Test Results have surpassed the minimum specified requirements with great margin*.

Secant-Pile Guide Wall Installation

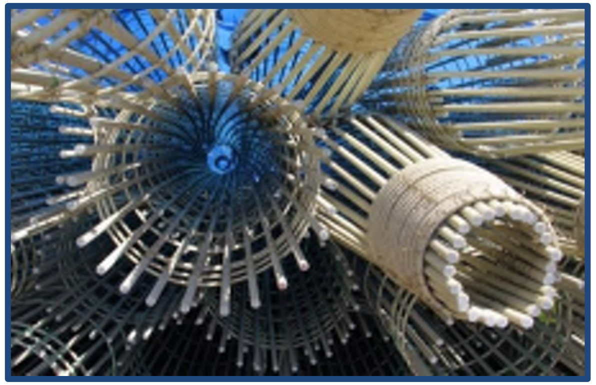


Secant-Pile guide-wall trench boxes were installed to assure alignment of piles

1,847 Secant-Piles were installed via guide-wall

Concrete pouring, i.e. flowable-fill was placed to complete the Secant-Pile layout locations

Removal of steel formwork, prior to drilling Secant-Piles



STATE ROAD A1A – SECANT-PILE WALL

The piles were designed with glass fiber-reinforced polymer (**GFRP**) rebar to eliminate the concern of corrosion and provide ***extended maintenance-free service life*** to minimize future needed construction activities along the coastal dune system.

Several "**Mitigation-Alternatives**" were carefully considered, after which the ***Secant-Pile*** system was selected and completed at the end of 2019. The secant-pile system *minimized the impact* on the existing sand dune-system during construction. Additionally, the *Piles are designed with GFRP* bars.

2019 Secant-Pile Seawall






Site assembled GFRP Cage-installations, at Flagler Beach, Florida

*The Seawall's **Auger-Cast Concrete Secant-Piles** are 36 in (910 mm) in diameter and the **Primary Piles** are 36 ft (11 m) in lengths and are reinforced with 25 No. 8 GFRP bars.*

Secant-Pile GFRP-Cage Installation Monitoring, QA/QC and Grout-Fluidifier Testing

1847 Secant-Piles were installed in only 4-1/2 Months for SR-A1A

1847 Secant-Piles were lifted, aligned, centered, and lowered into position

It should be noted that all pile centers have an accuracy of within 1-1/2 in (38 mm) in plan

Per FDOT Specifications, Section 455, Index E, grout needs a minimum standard flow rate of 15 seconds and achieve a minimum grout compressive strength of 4,000 psi (28 MPa).

Secant-Pile alignment and auger drilled soil removal, prior to concrete grouting

Laboratory and Field Testing of GFRP bars and Grout with Fluidifier

(i) ASTM C1611/C1611M
Standard Test Method for Slump Flow of Self-Consolidating Concrete (SCC)

(ii) ASTM C1621/C1621M
Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring

Secant-Pile Guide Wall and removal, Pile-cap, GFRP Placement and Dune-restoration

Removal of unreinforced concrete Guide-Wall, pile-cap GFRP placement, and final dune restoration/re-establishment atop the installed Secant-Pile Seawall/Bulkhead.

Life-Cycle-Cost Evaluation, with respect to GFRP bars, for this SR-A1A Project

Engineer's Estimate:

Traditional steel reinforced auger-cast pile = $191.50 / ft. length pile installed
GFRP-reinforced concrete auger-cast piles = $209.25 / ft. length pile installed

Assuming 75-year life for traditional RC = $2.55 /year/ft.
Assuming 100-year (min.) for GFRP-RC = $2.09 /year/ft. *(not considering reduced maintenance costs and environmental benefits) > 18% savings!*

***Note**: Engineer's Estimate, Bid-Quantities & Unit Costs obtained from FDOT.*

Bid Quantities & Unit Cost:

400-4-11	Class IV Concrete (Wall Cap) = (864 CY)($775/CY) = $669,600	Low Bid $415.00/CY =	$358,560
415-10-5	GFRP Reinforcing, #5 = (61892 LF)($1.37/LF) = $84,792	Low Bid $1.45/LF =	$89,743
455-112-6	Pile Auger Grouted, 36" Dia. = (51724 LF)($209.25) = $10,823,247	Low Bid $156.50/LF =	$8,094,806

Total Proposal Budget Estimate = $27,276,946 **Low Bid = $22,429,705**

GFRP - PRO’s

- Seawalls, Piles, and Piers
- Marine Structures
- “Quick” installation
- Light weight installation
- Assembly time savings
- “Toe” or “No-Toe” option
- GFRP cages remain in-place, i.e. “no flotation” observed
- Resilient, durable and extended Life-Cycle

GFRP - CON’s

- “Bent-Shapes” need to be Manufacturer fabricated
- No “on-site” bending of GFRP
- GFRP bars can contribute to “skin-itching” due to presence of Glass-Fibers (protective clothes beneficial)
- Typically more GFRP bars are needed than black steel rebars
- Currently not many GFRP design guidelines are readily available, in design software, but “in-progress” and developing fairly “rapidly”

Added Benefits of GFRP Installations, as validated by this SR-A1A Project

- *There is a substantial benefit by utilizing GFRP in structural concrete, exposed to corrosive environments*
- *Economics of GFRP comparable to "black steel" upfront costs and Return On Investment (ROI) is higher on a Life-Cycle Cost Analysis basis*
- *GFRP is anisotropic and linear-elastic up to failure*
- *Currently Specifications and Design Guidelines exist*
- *Light weight of GFRP translates into time-savings during assembly and significant material shipping cost reduction*

- The GFRP bars have a high tensile strength, low weight, and are noncorrosive
- The cage installations were smooth and rapid, and maintenance and repair costs over the life cycle of the seawall are expected to be minimal
- The durable materials in the wall will provide an extended time window for restoration activities, with a longer Service-Life

***Note*: Pictures show Secant-Pile installation atop Dune-System.**

Findings of GFRP Installations specific to the SR-A1A Project

- *No Secant-Pile cage alterations were needed. Installed all 1,847 Piles as intended during the design-phase. No alterations needed*
- *Quick and reliable Secant-Pile installation in soft to medium dense sands, during this State Road A1A (SR-A1A) project*
- *GFRP cage-assemblies resulted in up to 52% of time savings over "black steel" rebar cage construction*
- *Toe assemblies may be removed on future projects providing the integrity of grout hole stability remains in-place and EOR approves*
- *Less noise pollution (as field measured for this project) through Secant-Pile installation vs. Sheet-Pile installation*

***Note**: As an added feature, **sustainability**, **reliability**, **durability** and **resiliency** are all associated with the use of **GFRP**.*

Acknowledgments

We would like to thank the entire State Road A1A (SR-A1A) GFRP Secant-Pile design and construction team, inspectors and researchers, as well as all the individuals that have been actively involved and contributed to this unique and innovative project. A special thanks to:

- Florida Department of Transportation (FDOT)
- Superior Construction Southeast
- Malcolm Drilling Company
- RS&H
- Mott McDonald Florida
- Atkins
- Pultrall, Inc.
- Titan Concrete
- UM Dept. of Civil, Arch. and Env. Engineering
- University of Miami

5,000 Feet (1.6 km) GFRP-RC Seawall/Bulkhead protects State Highway A1A along Flagler Beach, Florida - USA

Questions?

Christian C. Steputat, P.E.
E-mail: csteputat@miami.edu

Thank U

Next Generation GFRP Bar properties & Implementation Economics

Doug Gremel – Director Engineering

Owens Corning Infrastructure Solutions

HOW WE
BUILD NOW

REVIEW OF BASICS

- Tensile Modulus or Youngs Modulus – strain exerted by a force stretching or contracting material
- Modulus of elasticity, $\mathrm{E} = \frac{\sigma}{\varepsilon}$

  Stress, $\sigma = \frac{\text{Force}}{\text{Area}}$

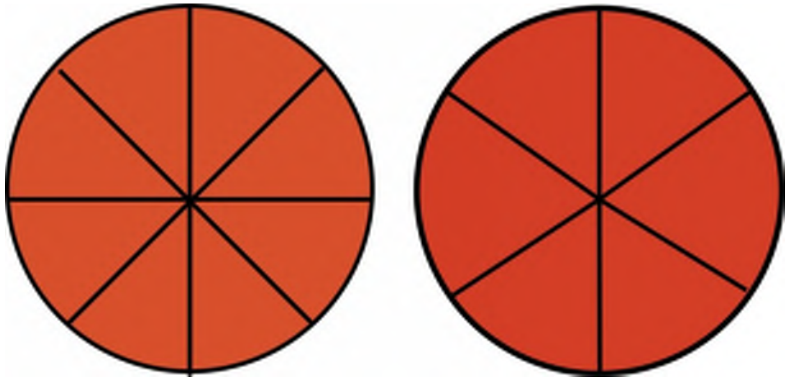
  Strain, $\varepsilon = \frac{\Delta l}{l}$

- E = tensile stress/tensile strain
  - E = (FL) / (A * change in L),
    - where F is the applied force, L is the initial length, A is the square area, and E is Young's modulus
  - Tensile stress = Force (ultimate load) / cross sectional area

- Small changes in AREA have a BIG effect on the modulus

PAST SITUATION – UNDER REPORTING CROSS SECTIONAL AREA

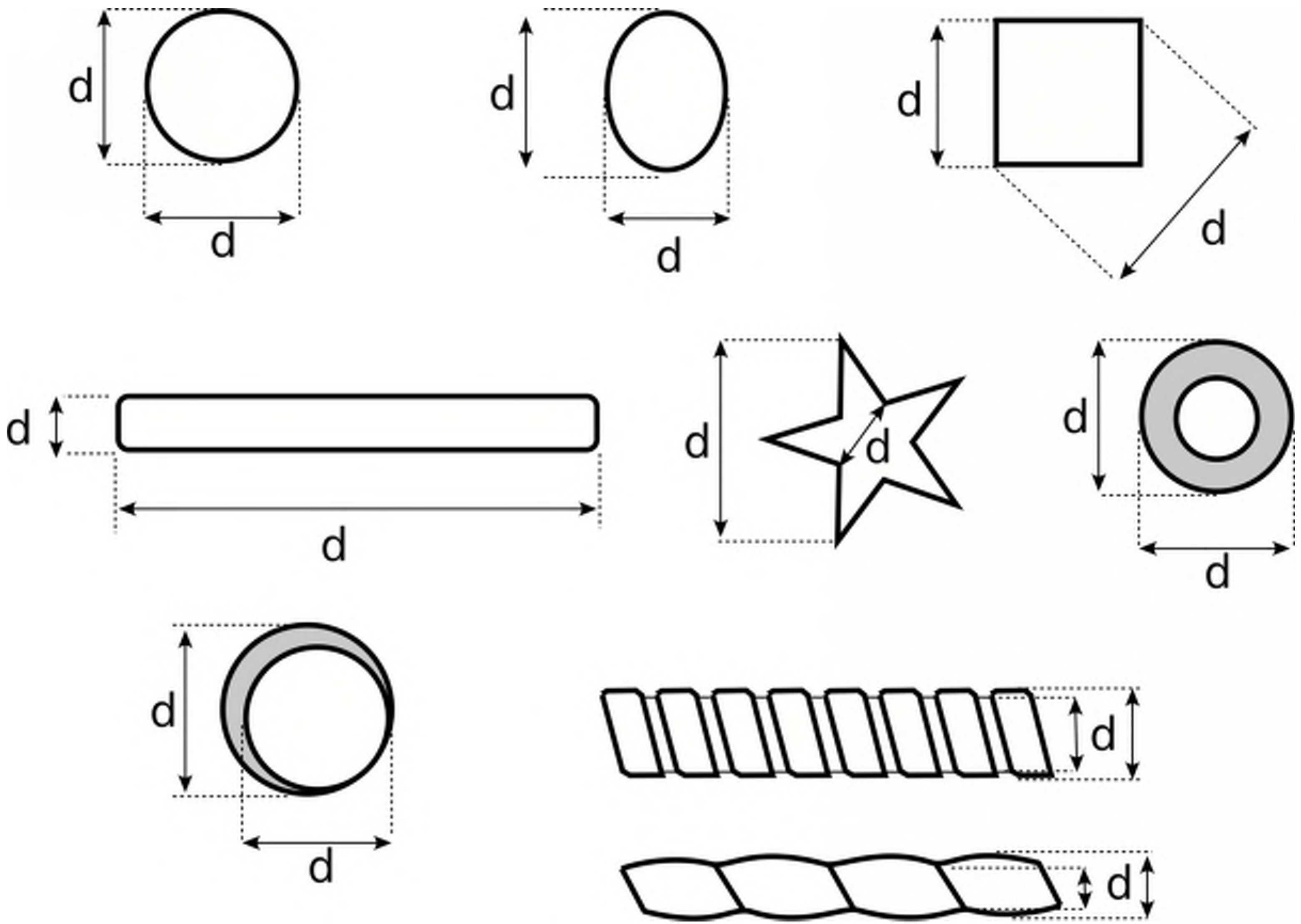
- Inflates properties
- *Not transparent* to the designer
- Can affect the design of the beam or slab
- Affects clear cover & bar spacing
- Credibility of industry



Is an 8 slice pizza bigger than an 6 slice pizza ?

Before industry standards

DIAMETER & AREA OF FIBERGLASS BARS



AREA OF FIBERGLASS BAR IS IMPORTANT

- Archimedes Principle
  - The buoyant force on a submerged object is equal to the weight of the liquid displaced. See ASTM D7205

Effect of area on modulus
0.104 in^2 vs 0.161 in^2

Example shows upper & lower tolerances of ASTM D7957 **measured cross sectional area** on #3 (10mm) bar

ASTM D7957 – IMPORTANT INDUSTRY CONSENSUS

In ASTM D7957 we agreed as an industry to use “nominal area” for determination of properties WITH a tolerance to accommodate surface enhancements for bond.

- Nominal based on pure cylinder area for all calcs
- “measured cross sectional area” with a tolerance for bond enhancement, out of round, irregular surface… etc
- Set a path for true improvements which have occurred

NOMINAL VS "MEASURED AREA"

- To account for "surface enhancements"…
  - Ribs (height or depth & width of ribs)
  - Sand coating (size of sand grains)
  - Lugs / undulations between external wraps

- Reason for a "tolerance" from nominal
- ASTM D7957

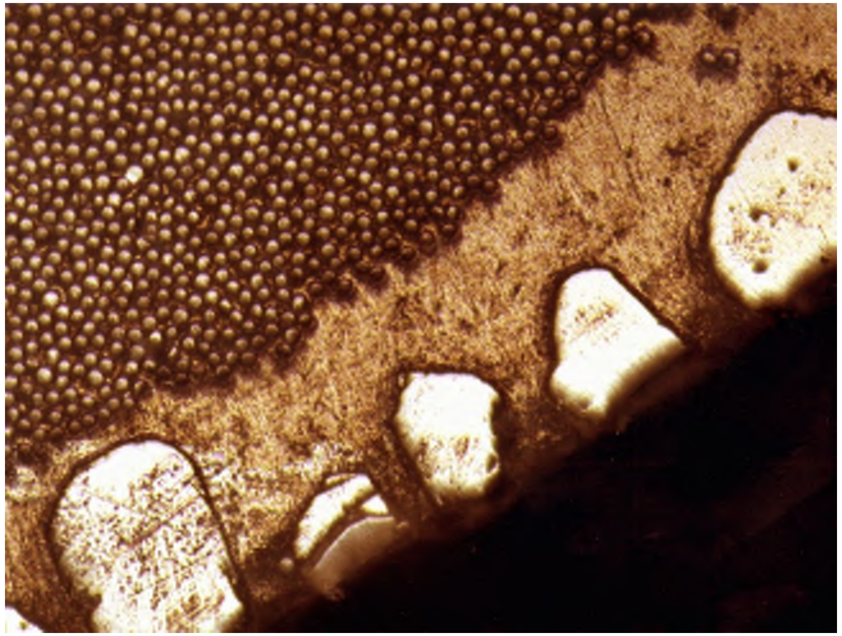
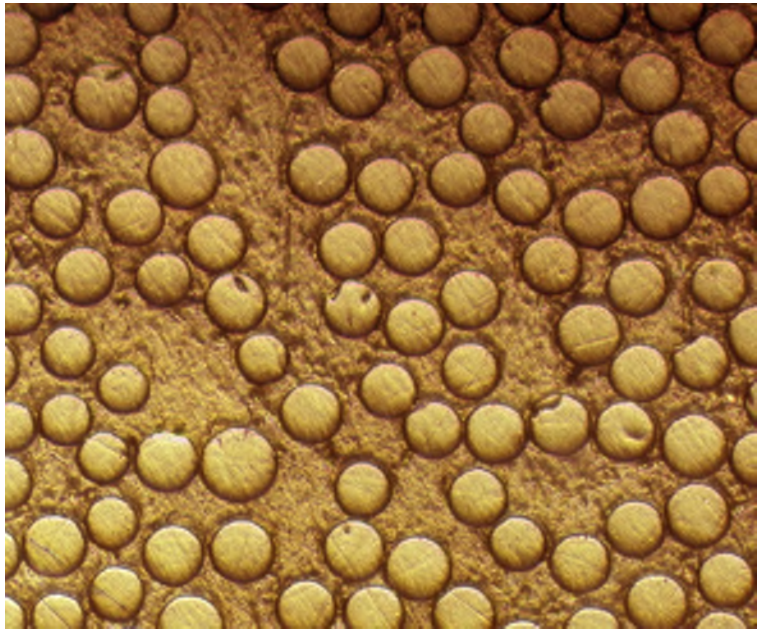


TABLE 3 Geometric and Mechanical Property Requirements

Bar Designation No.	Nominal Dimensions		Measured Cross-Sectional Area Limits mm² [in.²]		Minimum Guaranteed Ultimate Tensile Force kN [kip]
	Diameter mm [in.]	Cross-Sectional Area mm² [in.²]	Minimum	Maximum	
M6 [2]	6.3 [0.250]	32 [0.049]	30 [0.046]	55 [0.085]	27 [6.1]
M10 [3]	9.5 [0.375]	71 [0.11]	67 [0.104]	104 [0.161]	59 [13.2]
M13 [4]	12.7 [0.500]	129 [0.20]	119 [0.185]	169 [0.263]	96 [21.6]
M16 [5]	15.9 [0.625]	199 [0.31]	186 [0.288]	251 [0.388]	130 [29.1]
M19 [6]	19.1 [0.750]	284 [0.44]	268 [0.415]	347 [0.539]	182 [40.9]
M22 [7]	22.2 [0.875]	387 [0.60]	365 [0.565]	460 [0.713]	241 [54.1]
M25 [8]	25.4 [1.000]	510 [0.79]	476 [0.738]	589 [0.913]	297 [66.8]
M29 [9]	28.7 [1.128]	645 [1.00]	603 [0.934]	733 [1.137]	365 [82.0]
M32 [10]	32.3 [1.270]	819 [1.27]	744 [1.154]	894 [1.385]	437 [98.2]

MODULUS – A FUNCTION OF GLASS CONTENT & AREA



Rule of Mixtures says

$E_c = fE_f + (1\text{-}f)E_m$ where:

- f = volume fraction of fibers
- E_f = E-Modulus of the fibers
- E_m = E-Modulus of the matrix

How much glass you can pack into a given area = Modulus

NEW DOCUMENTS

- Hi-Mod Straight bars with minimum E-modulus of 8.75 msi (60GPa)
- Hi-Mod Fabricated bends with minimum E-modulus of 7.5msi (52GPa)

- Processes are different for most producers
- Physical & mechanical properties are different

- Highlights differences to the Designer

HI-MOD STRAIGHT BAR DRAFT

INTERNATIONAL Designation: DXXXX/DXXXXM –

Date:	<Enter Date>
To:	Subcommittee <AXX.XX> or Main Committee <AXX> members (both for concurrent ballots)
Tech Contact:	<Contact Name, email address/phone number>
Work Item #:	<Enter Work Item number>
Ballot Action:	Revision of <Enter Standard Designation/Title>
Rationale:	<Enter reasons for proposed ballot action. Include an update on previous ballot history, if applicable>

Standard Specification for
Solid Round, High Modulus Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement in Straight Lengths[1]

- Key Differences with ASTM D7957
  - Limits are higher for tensile modulus
  - Increased limits on tensile properties
  - Removes all references to bends (helps provide clarity)
  - Adds apparent shear (short beam) test
  - Better resolution on bond strength & strain by bar diameter
  - Adds epoxy resin **if** it meets durability criteria
- Similarities with ASTM D7957
  - Uses same “measured area” tolerances as existing ASTM D7957
  - Limits on Tensile strength & other parameters mirror CSA S807-19

HI-MOD FABRICATED BENT BAR DRAFT

Designation: DYYYY/DYYYYM –

Date:	<Enter Date>
To:	Subcommittee <AXX.XX> or Main Committee <AXX> members (both for concurrent ballots)
Tech Contact:	<Contact Name, email address/phone number>
Work Item #:	<Enter Work Item number>
Ballot Action:	Revision of <Enter Standard Designation/Title>
Rationale:	<Enter reasons for proposed ballot action. Include an update on previous ballot history, if applicable>

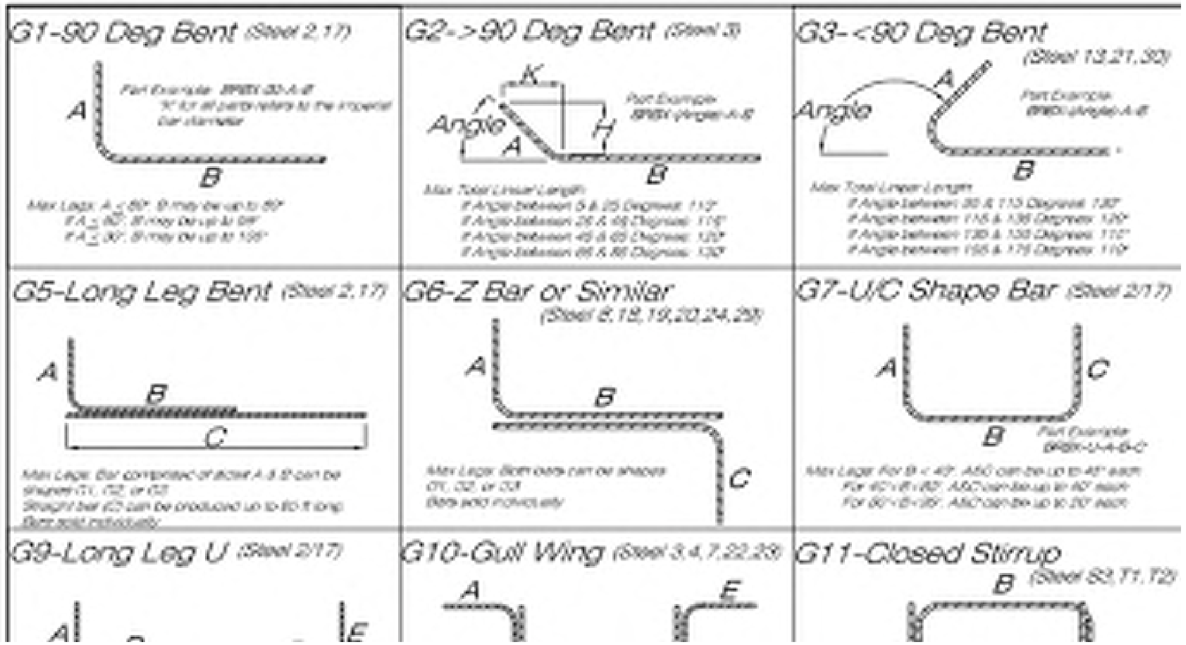
Standard Specification for
Solid RoundGlass Fiber Reinforced Polymer Bars for Concrete Reinforcement in Fabricated Bent Shapes[1]

- Key Differences with ASTM D7957
  - Limits on Tensile strength & other parameters mirror CSA S807-19 for Grade II bends
  - Should provide clarity on bent bar properties and QC/QA
    - Defines lot size based on resin batch, not by shape !
    - Strength of straight portion of a bent bar
    - Strength of the bent portion of a bent bar
  - Better resolution on bond strength & strain by bar diameter
  - Adds epoxy resin **if** it meets durability criteria

- Similarities with ASTM D7957
  - Uses same "measured area" tolerances as existing ASTM D7957
  - Limits on Tensile strength & other parameters mirror CSA S807-19

HI-MOD FABRICATED BENT BAR DRAFT

- Introduces “shape codes” and detailing guide similar to steel shape codes



DEFINING “LIMITS” FOR BARS

Straight

TABLE 3 Geometric and Mechanical Property Requirements

Bar Designation No.	Nominal Dimensions		Measured Cross-Sectional Area Limits mm² [in.²]		Minimum Guaranteed Ultimate Tensile Force kN [kip]	Minimum Guaranteed Ultimate Tensile Strength MPa [ksi]	Ultimate Tensile Strain %	Bond Strength MPa [ksi]
	Diameter mm [in.]	Cross-Sectional Area mm² [in.²]	Minimum	Maximum				
M6 [2]	6.3 [0.250]	32 [0.049]	30 [0.046]	55 [0.085]	?	?	?	12.4[1.8]
M10 [3]	9.5 [0.375]	71 [0.11]	67 [0.104]	104 [0.161]	71 [16]	1000 [145]	1.7%	12.4[1.8]
M13 [4]	12.7 [0.500]	129 [0.20]	119 [0.185]	169 [0.263]	129 [29]	1000 [145]	1.7%	10.3[1.5]
M16 [5]	15.9 [0.625]	199 [0.31]	186 [0.288]	251 [0.388]	200 [45]	1000 [145]	1.7%	10.3[1.5]
M19 [6]	19.1 [0.750]	284 [0.44]	268 [0.415]	347 [0.539]	255 [57]	900 [130]	1.5%	9.6[1.4]
M22 [7]	22.2 [0.875]	387 [0.60]	365 [0.565]	460 [0.713]	334 [75]	862 [125]	1.5%	9.6[1.4]
M25 [8]	25.4 [1.000]	510 [0.79]	476 [0.738]	589 [0.913]	422 [95]	827 [120]	1.4%	7.6[1.1]
M29 [9]	28.7 [1.128]	645 [1.00]	603 [0.934]	733 [1.137]	?	?	?	7.6[1.1]
M32 [10]	32.3 [1.270]	819 [1.27]	744 [1.154]	894 [1.385]	?	?	?	7.6[1.1]

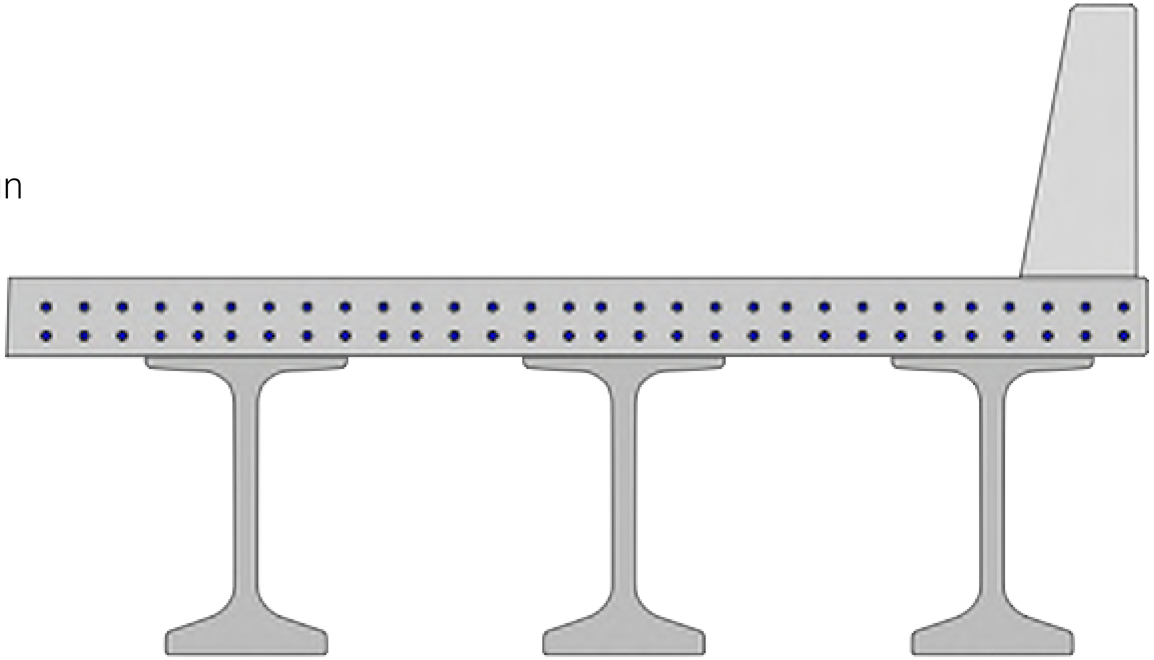
Bends

TABLE 3 Geometric and Mechanical Property Requirements

Bar Designation No.	Nominal Dimensions		Measured Cross-Sectional Area Limits mm² [in.²]		Minimum Guaranteed Ultimate Tensile Force kN [kip]	Minimum Guaranteed Ultimate Tensile Strength MPa [ksi]	Ultimate Tensile Strain %	Bond Strength MPa [ksi]
	Diameter mm [in.]	Cross-Sectional Area mm² [in.²]	Minimum	Maximum				
M6 [2]	6.3 [0.250]	32 [0.049]	30 [0.046]	55 [0.085]	?	?	?	?
M10 [3]	9.5 [0.375]	71 [0.11]	67 [0.104]	104 [0.161]	71 [16]	1000 [145]	1.9%	12.4[1.8]
M13 [4]	12.7 [0.500]	129 [0.20]	119 [0.185]	169 [0.263]	129 [29]	1000 [145]	1.9%	10.3[1.5]
M16 [5]	15.9 [0.625]	199 [0.31]	186 [0.288]	251 [0.388]	200 [45]	1000 [145]	1.9%	10.3[1.5]
M19 [6]	19.1 [0.750]	284 [0.44]	268 [0.415]	347 [0.539]	255 [57]	900 [130]	1.7%	9.6[1.4]
M22 [7]	22.2 [0.875]	387 [0.60]	365 [0.565]	460 [0.713]	334 [75]	862 [125]	1.7%	9.6[1.4]
M25 [8]	25.4 [1.000]	510 [0.79]	476 [0.738]	589 [0.913]	422 [95]	827 [120]	1.6%	7.6[1.1]

HOW IMPROVED PROPERTIES AFFECT DESIGN –
BRIDGE DECK EXAMPLE

- Variables
  - Girder Spacing
  - Design methodology
    - Flexural Unit Strip
    - Arching action with restraint – Empirical design
  - Concrete Strength
  - Concrete Cover
  - Deck Thickness
  - GFRP bar modulus
  - Reinforcing area – bar spacing
    - Transverse
    - Longitudinal
  - Crack Widths
  - Deflection
  - Girder type
  - Cantilever overhang
  - Span type
    - Simply supported
    - Continuous with negative moment
  - Barrier size
  - Bond depended coefficient Kb
  - Etc etc



ASTMD7957 PROPERTIES – USING FLEXURAL UNIT STRIP METHODOLOGY

- AASHTO Table A4-1
  - Same Top and Bottom Spacing
  - Bottom Longitudinal 66% of Transverse
  - Top Longitudinal S & T
  - 2 Bar Diameter Clear Cover

ASTM Deck Design Table

Effective Span Length (ft)	Deck Thickness (in)	Transverse Bars				Longitudinal Bars				ASTM Total (in^2/ft^2)
		Top Bars		Bottom Bars		Top Bars		Bottom Bars		
		Size	Spa (in)	Size	Spa (in)	Size	Spa (in)	Size	Spa (in)	
7	8.50	#5	5.75	#5	5.75	#4	11.00	#5	8.63	1.92
7.5	8.50	#5	5.75	#5	5.75	#4	11.00	#5	8.63	1.92
8	8.50	#5	5.50	#5	5.50	#4	11.00	#5	8.25	1.99
8.5	8.50	#5	5.50	#5	5.50	#4	11.00	#5	8.25	1.99
9	8.75	#5	5.50	#5	5.50	#4	11.00	#5	8.25	1.99
9.5	9.00	#5	5.25	#5	5.25	#4	11.00	#5	7.88	2.08
10	9.00	#5	5.00	#5	5.00	#4	11.00	#5	7.50	2.17
10.5	9.25	#5	4.75	#5	4.75	#4	11.00	#5	7.13	2.28
11	9.50	#5	4.75	#5	4.75	#4	11.00	#5	7.13	2.28
11.5	9.50	#5	4.50	#5	4.50	#4	11.00	#5	6.75	2.39
12	9.75	#5	4.50	#5	4.50	#4	11.00	#5	6.75	2.39
12.5	10.00	#5	4.25	#5	4.25	#4	11.00	#5	6.38	2.52

Calculations courtesy of Koch Structures

USING PROPOSED ASTM HI-MOD STRAIGHT BAR PROPERTIES

Gen II Deck Design Table										
Effective Span Length (ft)	Deck Thickness (in)	Transverse Bars				Longitudinal Bars				Gen II Total (in^2/ft^2)
		Top Bars		Bottom Bars		Top Bars		Bottom Bars		
		Size	Spa (in)	Size	Spa (in)	Size	Spa (in)	Size	Spa (in)	
7	8.50	#5	7.00	#5	7.00	#4	11.00	#5	10.50	1.61
7.5	8.50	#5	6.50	#5	6.50	#4	11.00	#5	9.75	1.72
8	8.50	#5	6.50	#5	6.50	#4	11.00	#5	9.75	1.72
8.5	8.50	#5	6.25	#5	6.25	#4	11.00	#5	9.38	1.78
9	8.75	#5	6.25	#5	6.25	#4	11.00	#5	9.38	1.78
9.5	9.00	#5	6.25	#5	6.25	#4	11.00	#5	9.38	1.78
10	9.00	#5	6.00	#5	6.00	#4	11.00	#5	9.00	1.85
10.5	9.25	#5	5.75	#5	5.75	#4	11.00	#5	8.63	1.92
11	9.50	#5	5.50	#5	5.50	#4	11.00	#5	8.25	1.99
11.5	9.50	#5	5.25	#5	5.25	#4	11.00	#5	7.88	2.08
12	9.75	#5	5.25	#5	5.25	#4	11.00	#5	7.88	2.08
12.5	10.00	#5	5.25	#5	5.25	#4	11.00	#5	7.88	2.08

Calculations courtesy of Koch Structures

SAVINGS WITH BETTER BAR PROPERTIES –

UNIT STRIP FLEXURAL DESIGN

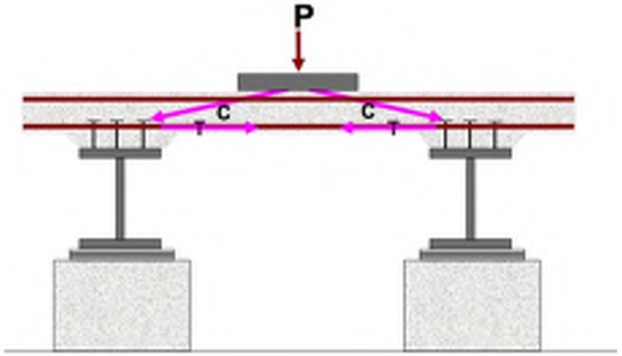
- Increased Bar Spacing for ALL spans
  - Average Transverse Increase 18%
- Reduction In Total Reinforcing Area for ALL girder spacings
- Average Reduction 14%

Summary		
Gen II	ASTM	Reduction
Total (in^2/ft^2)	Total (in^2/ft^2)	(%)
1.61	1.92	15.87%
1.72	1.92	10.25%
1.72	1.99	13.74%
1.78	1.99	10.71%
1.78	1.99	10.71%
1.78	2.08	14.36%
1.85	2.17	15.03%
1.92	2.28	15.76%
1.99	2.28	12.35%
2.08	2.39	13.01%
2.08	2.39	13.01%
2.08	2.52	17.43%

Calculations courtesy of Koch Structures

ASTMD7957 PROPERTIES – USING EMPIRICAL DESIGN METHOD

considers arching action outside of cantilevers, internally restrained



- Reinforcing Calculated with Ratios
  - Bottom Transverse – Stiffness Driven
  - Other 3 layers r = .0035
  - 2 Bar Diameter Clear Cover

ASTM Deck Design Table Empirical Method										
Effective Span Length (ft)	Deck Thickness (in)	Transverse Bars				Longitudinal Bars				ASTM Total (in^2/ft^2)
		Top Bars		Bottom Bars		Top Bars		Bottom Bars		
		Size	Spa (in)	Size	Spa (in)	Size	Spa (in)	Size	Spa (in)	
7	8.50	#5	10.25	#6	6.25	#5	10.25	#5	10.25	1.92
7.5	8.50	#5	10.25	#6	6.25	#5	10.25	#5	10.25	1.92
8	8.50	#5	10.25	#6	6.25	#5	10.25	#5	10.25	1.92
8.5	8.50	#5	10.25	#6	6.25	#5	10.25	#5	10.25	1.92
9	8.75	#5	10.00	#6	6.00	#5	10.00	#5	10.00	1.98
9.5	9.00	#5	9.75	#6	5.75	#5	9.75	#5	9.75	2.05
10	9.00	#5	9.75	#6	5.75	#5	9.75	#5	9.75	2.05
10.5	9.25	#5	9.50	#6	5.50	#5	9.50	#5	9.50	2.12
11	9.50	#5	9.25	#6	5.25	#5	9.25	#5	9.25	2.20
11.5	9.50	#5	9.25	#6	5.25	#5	9.25	#5	9.25	2.20
12	9.75	#5	9.00	#6	5.25	#5	9.00	#5	9.00	2.23
12.5	10.00	#5	8.75	#6	5.00	#5	8.75	#5	8.75	2.31

Calculations courtesy of Koch Structural Solutions

PROPOSED ASTM HI-MOD– EMPIRICAL METHODOLOGY

Gen II Deck Design Table Empirical Method										
Effective Span Length (ft)	Deck Thickness (in)	Transverse Bars				Longitudinal Bars				Gen II Total (in^2/ft^2)
		Top Bars		Bottom Bars		Top Bars		Bottom Bars		
		Size	Spa (in)	Size	Spa (in)	Size	Spa (in)	Size	Spa (in)	
7	8.50	#5	10.25	#6	8.00	#5	10.25	#5	10.25	1.73
7.5	8.50	#5	10.25	#6	8.00	#5	10.25	#5	10.25	1.73
8	8.50	#5	10.25	#6	8.00	#5	10.25	#5	10.25	1.73
8.5	8.50	#5	10.25	#6	8.00	#5	10.25	#5	10.25	1.73
9	8.75	#5	10.00	#6	7.75	#5	10.00	#5	10.00	1.78
9.5	9.00	#5	9.75	#6	7.50	#5	9.75	#5	9.75	1.83
10	9.00	#5	9.75	#6	7.50	#5	9.75	#5	9.75	1.83
10.5	9.25	#5	9.50	#6	7.25	#5	9.50	#5	9.50	1.89
11	9.50	#5	9.25	#6	7.00	#5	9.25	#5	9.25	1.96
11.5	9.50	#5	9.25	#6	7.00	#5	9.25	#5	9.25	1.96
12	9.75	#5	9.00	#6	6.75	#5	9.00	#5	9.00	2.01
12.5	10.00	#5	8.75	#6	6.50	#5	8.75	#5	8.75	2.07

Calculations courtesy of Koch Structural Solutions

SUMMARY EMPIRICAL DESIGN METHOD

- Increased Bar Spacing for ALL spans
  - Average Transverse Increase 30%
- Reduction In Total Reinforcing Area for ALL girder spacings
- Average Reduction 10%

Summary Empirical Method		
Gen II	ASTM	Reduction (%)
Total (in^2/ft^2)	Total (in^2/ft^2)	
1.73	1.92	9.63%
1.73	1.92	9.63%
1.73	1.92	9.63%
1.73	1.92	9.63%
1.78	1.98	10.03%
1.83	2.05	10.46%
1.83	2.05	10.46%
1.89	2.12	10.93%
1.95	2.20	11.45%
1.95	2.20	11.45%
2.01	2.23	10.02%
2.07	2.31	10.53%

Calculations courtesy of Koch Structural Solutions

OTHER FACTORS AFFECTING DESIGN OPTIMIZATION

- Larger total reduction in bar area if top & bottom mat are designed separately
- More improvement in bar spacing gained if:
  - Crack Width is increased from 0.020”(0.5mm) to 0.028”(0.71mm)
    - Now in AASHTO 2019 Guide Spec GFRP LRFD design 2nd edition
  - Improve default bond dependent factor C_b = 0.833 (K_b =1.2)
- Temperature & Shrinkage equations could be updated to take into account improvements in tensile modulus
- Empirical design methodology (*arching action, restrained at girders except cantilevers*) much more economical that Unit Strip method

OHIO DOT – BRIDGE DECK DRAFT STANDARDS

- Uses proposed revised properties *(As does Florida DOT)*
- Same reinforcing area implementation as steel rebar
  - Up to 12.5ft girder spacing

Current ODOT BDM Deck Design Table									
Effective Span Length (ft)	Deck Thickness (in)	Transverse Bars				Longitudinal Bars			
		Top Bars		Bottom Bars		Top Bars		Bottom Bars	
		Size	Spa (in.)	Size	Spa (in.)	Size	Spa (in.)	Size	Spa (in.)
7.0	8.50	#5	6.00	#5	6.00	#4	12.50	#5	10.75
7.5	8.50	#5	6.00	#5	6.00	#4	12.00	#5	10.25
8.0	8.50	#5	6.00	#5	6.00	#4	11.50	#5	9.75
8.5	8.50	#5	5.75	#5	5.75	#4	11.00	#5	9.25
9.0	8.75	#5	5.75	#5	5.75	#4	11.00	#5	9.25
9.5	9.00	#5	5.75	#5	5.75	#4	11.00	#5	9.25
10.0	9.00	#5	5.25	#5	5.25	#4	10.00	#5	8.75
10.5	9.25	#5	5.25	#5	5.25	#4	10.00	#5	8.75
11.0	9.50	#5	5.00	#5	5.00	#4	9.50	#5	8.75
11.5	9.50	#6	5.75	#5	5.75	#4	7.75	#5	8.75
12.0	9.75	#6	5.75	#5	5.75	#4	7.75	#5	8.75
12.5	10.00	#6	5.75	#5	5.75	#4	7.75	#5	8.75

Current draft Ohio DOT bridge deck standard

CANADIAN CHBDC CSA S6-06 CREDIT BENMOKRANE 2009

- 2009 Benmokrane showed effects of deck design with 3 varying GFRP bar modulus

Table 2 Mechanical properties of GFRP bars used in this investigation

Type of GFRP bars	Area (mm^2)	Specified tensile strength, f_{FRPu} (MPa)	Tensile modulus of elasticity, E_{FRP} (MPa)
A (low)	198	655	40800
B (medium)	198	683	48200
C (high)	198	1250	64200

FRPRCS-9 Sydney Australia "Design of Concrete Bridge Deck Slabs using Different Types of GFRP Bars" - Sherif El-Gamal, Brahim Benmokrane

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CANADIAN CHBDC CSA S6-06 CREDIT BENMOKRANE 2009

- CSA Empirical design method – considers arching action outside of cantilevers
- Reinforcing ratio directly related to bar modulus
- Bar tensile strength & concrete strength do NOT affect design
- Cover & Deck Thickness along with bar modulus drive design implementation
- Kb =0 .8

Table 2: Mechanical properties of sand-coated GFRP bars used in this investigation

Type of GFRP bars	Grade*	Nominal area** (mm^2)	Specified tensile strength, f_{FRPu} (MPa)	Tensile modulus of elasticity, E_{FRP} (GPa)
G-I	I	199	940	42.5
G-II	II	199	1130	52.5
G-III	III	199	1184	62.6

* According to the CAN/CSA S807-10 (2010).
** Cross-sectional area of No. 15 GFRP bars (15.9 mm diameter) according to the CAN/CSA S807-10 (2010).

27% less reinforcing area in transverse direction with new standard properties

CANADIAN CHBDC CSA S6-06 CREDIT BENMOKRANE 2009

Using CSA S6 Flexural design method

- Designs limited by crack widths
- Increasing deck thickness reduces reinforcing area
- Girder spacing greatly affects implementation
- Increasing GFRP modulus decreases reinforcing area by varying amounts
- Used Bond Dependent Coefficient K_b = 0.80

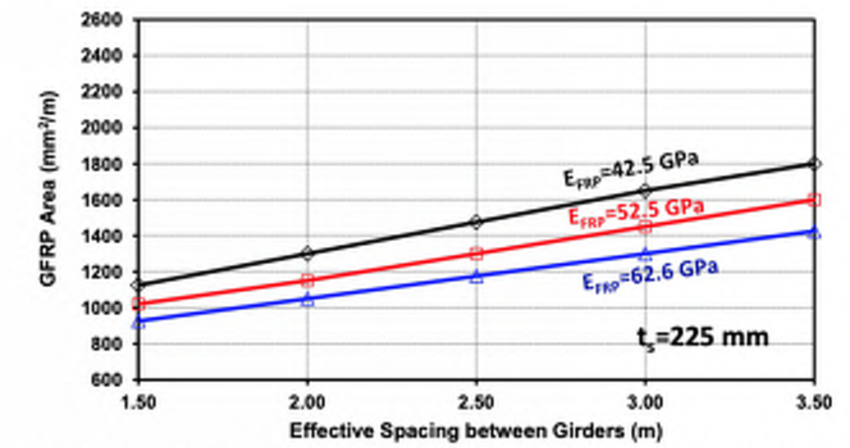


Figure 5: Area of the transverse GFRP reinforcement versus the effective spacing between girders

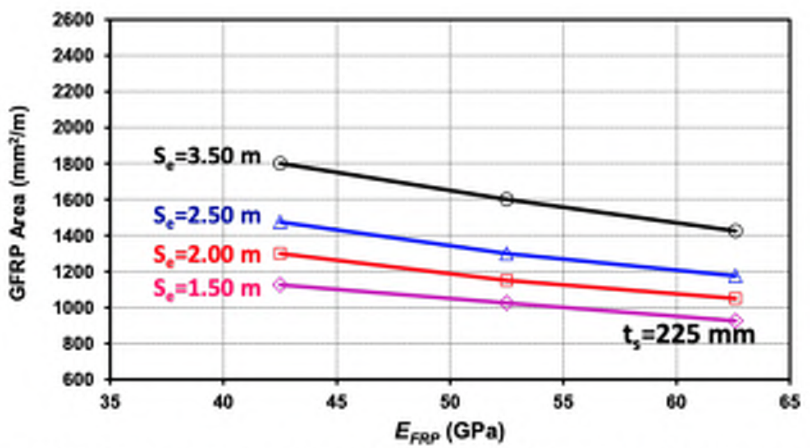
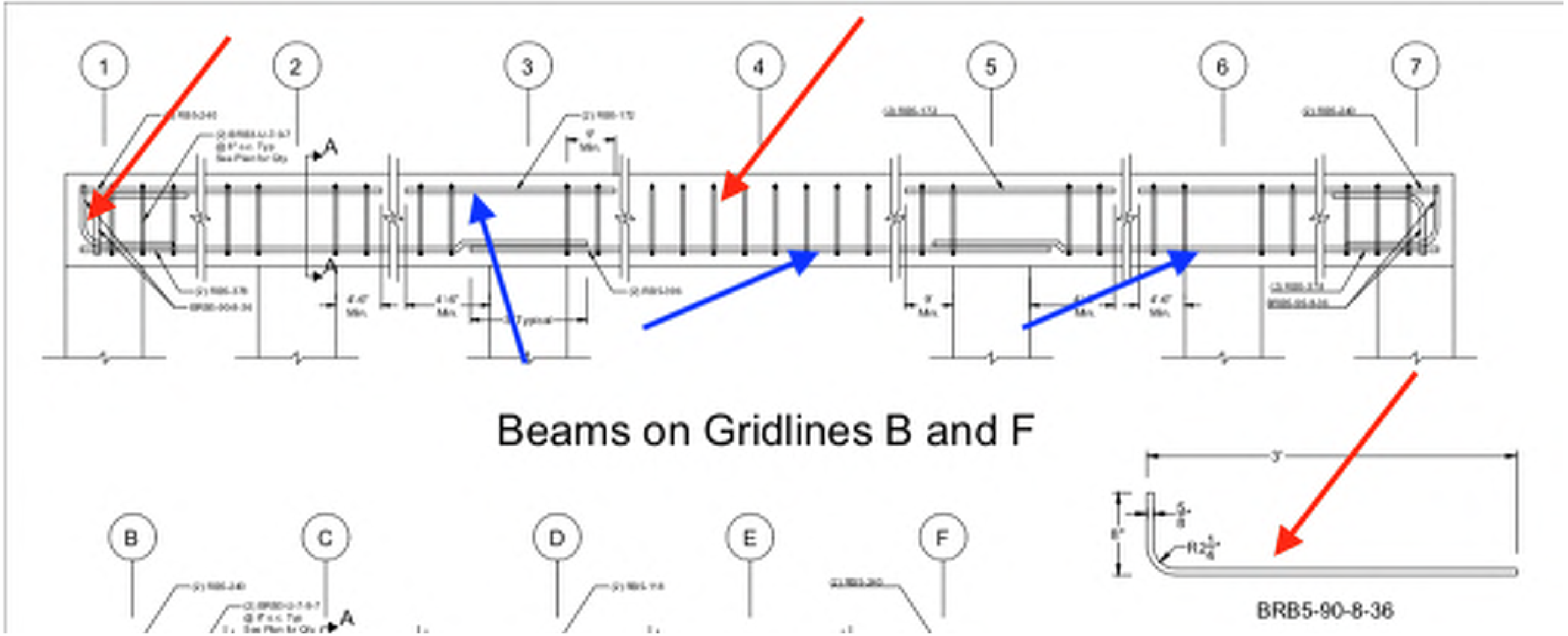


Figure 6: Area of the transverse GFRP reinforcement versus the modulus of elasticity of the GFRP bars

Rebar area decreased between 10% to 27%

IMPACT ON DESIGNER

- Must be aware of differing material properties
  - Straight Bar
  - Bent Bar



PROPOSED ASTM HI-MOD FIBERGLASS MATERIAL STANDARDS

- Possible due to industry consensus on bar area tolerances
- Improvements in manufacturing capabilities
  - Glass content above 83% makes possible
- Cost neutral improvements
  - Glass is LESS costly than resin !
- Improves economics of implementation by 10 to 27%
  - Design methodology matters (bridge deck example)
  - Bond dependent coefficient & crack widths still control design

INDUSTRY HAS WORK TO DO

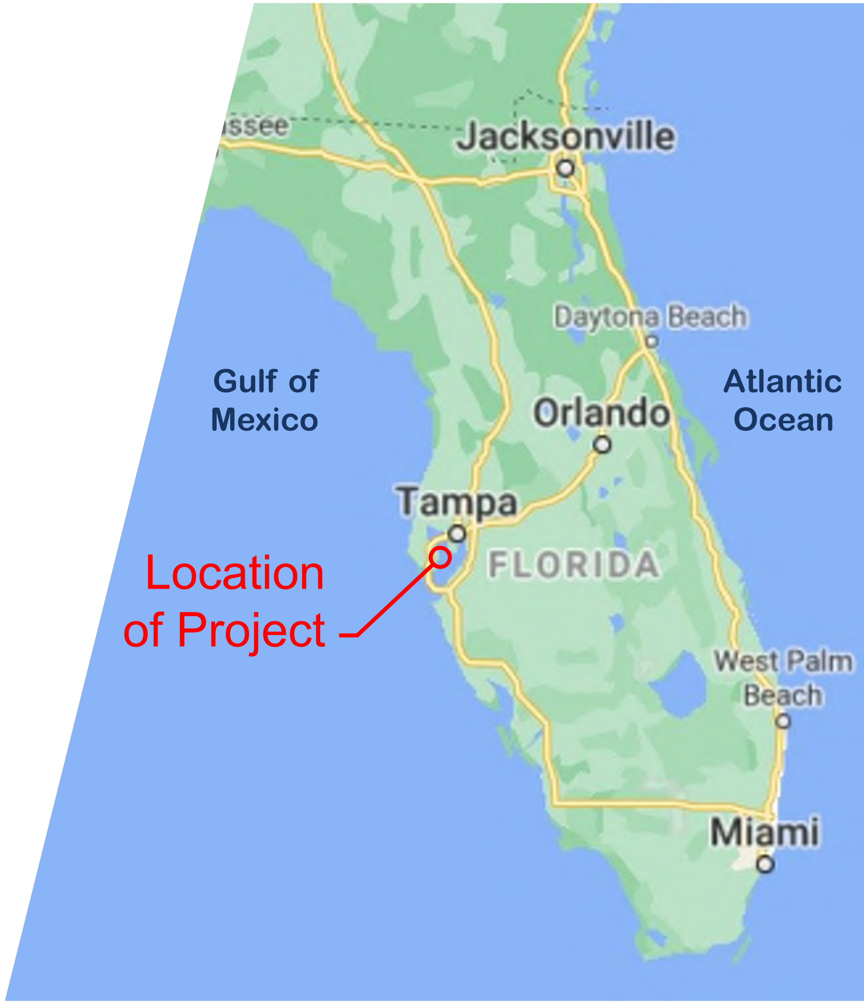
- Reach consensus on standards
- Prepare designers
- Validate proposed limits
  - Avoid flying too close to the sun

6-Span CFRP-PC/GFRP-RC Bridge over Placido Bayou

Christopher Gamache, P.E.
Ananda Bergeron, P.E.
Pooya Farahbakhsh, P.E.

Introduction

- Purpose of Project
  - Bridge replacement to address existing structural deterioration
- Project Location
  - City of St. Petersburg, Florida
  - 40^{th} Avenue NE over Placido Bayou
- Intent of Presentation
  - To provide illustrative example of a municipal bridge replacement utilizing FRP materials

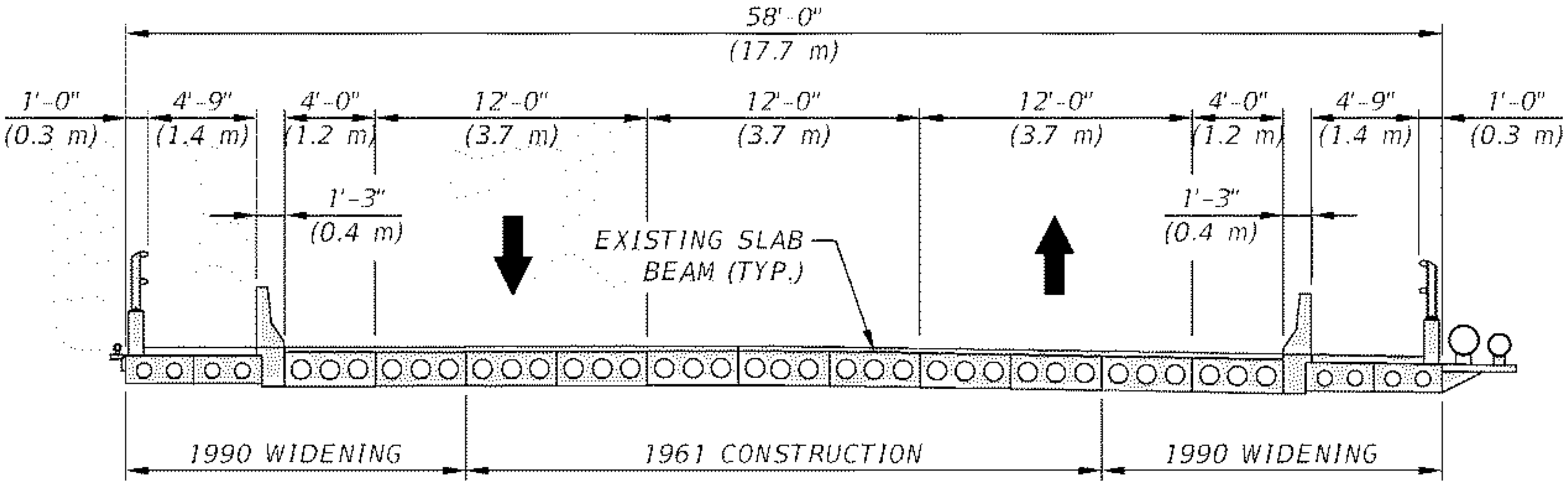


Background

- Existing Bridge
  - Nathanial J. Upham Bridge (No. 157154)
  - Owned/maintained by the City of St. Petersburg
  - Originally constructed in 1961
  - Widened in 1990
  - 58.0 ft (17.7 m) wide & 336.0 ft (102.4 m) long
  - 7 equal simple spans
  - Deck is comprised of butted prestressed voided slab beams
  - Maximum vertical clearance of 8.5 ft (2.6 m)

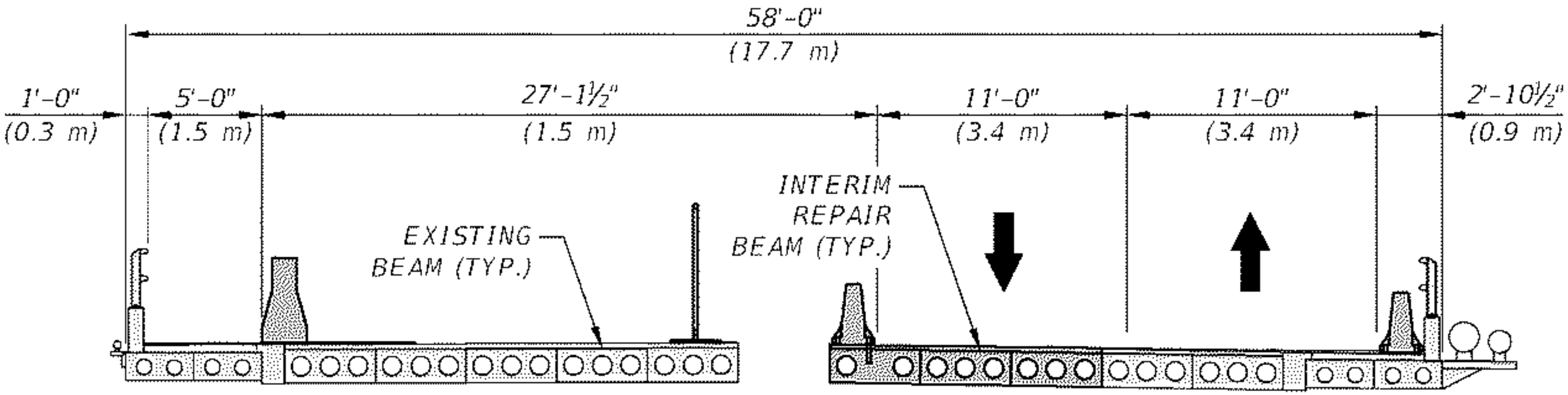
Background

> Existing Bridge Deficiencies
  - Categorized as Structurally Deficient
  - Deterioration in superstructure and substructure
  - Bridge Closed in August 2017 due to section loss in prestressing strands in 1961 beams in center span



Background

- Temporary Emergency Repairs
  - To maintain two lanes of traffic and a sidewalk
  - Three beams in the center span were replaced and transversely tied to the remaining existing beams



Design Approach

> Proposed Bridge
  - Prestressed Florida Slab Beam (FSB) Superstructure with cast-in-place topping slab
  - 57.8 ft (17.6 m) wide & 320.0 ft (97.5 m) long
  - 6 span structure
  - Prestressed pile bend substructure
  - Phased construction to maintain traffic
  - FRP sheet pile surrounding end bents and along approaches

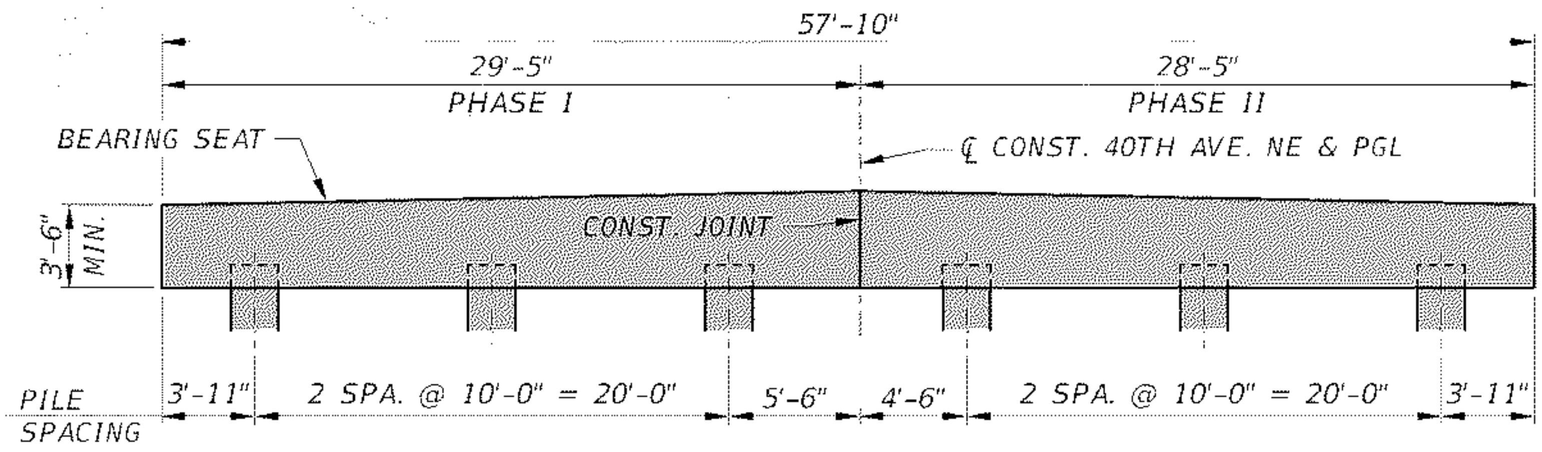
Design Approach

- Extremely Aggressive Environment
  - Within salt water splash zone
  - Vertical clearance varies from 7.0 ft (2.1 m) to 13.2 ft (4.0 m)
  - Design focused on concrete elements that are durable and resilient to salt water exposure
  - Accomplished by eliminating traditional carbon steel reinforcement and prestressing tendons with direct exposure to salt water
  - Direct exposure elements identified as bent piles, bent caps, sheet pile walls, beams, and topping slab
  - Design of FRP elements per
    - FDOT Fiber Reinforced Polymer Guidelines
    - AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete
    - AASHTO Guide Specifications for the Design of Concrete Bridge Beams Prestressed with CFRP Systems
    - ACI 440.4 Prestressing Concrete Structures with FRP Tendons

Design Approach

> Substructure Design

- Piles are prestressed 24” square.
- FDOT Standard Plans allowing for the Contractor to choose between either CFRP or stainless steel reinforcement and prestressing tendons in the piles
- Cast-in-place bent caps with GFRP reinforcement
- FRP pultruded sheet pile with a cast-in-place concrete cap were designed around the end bents and along the roadway approaches



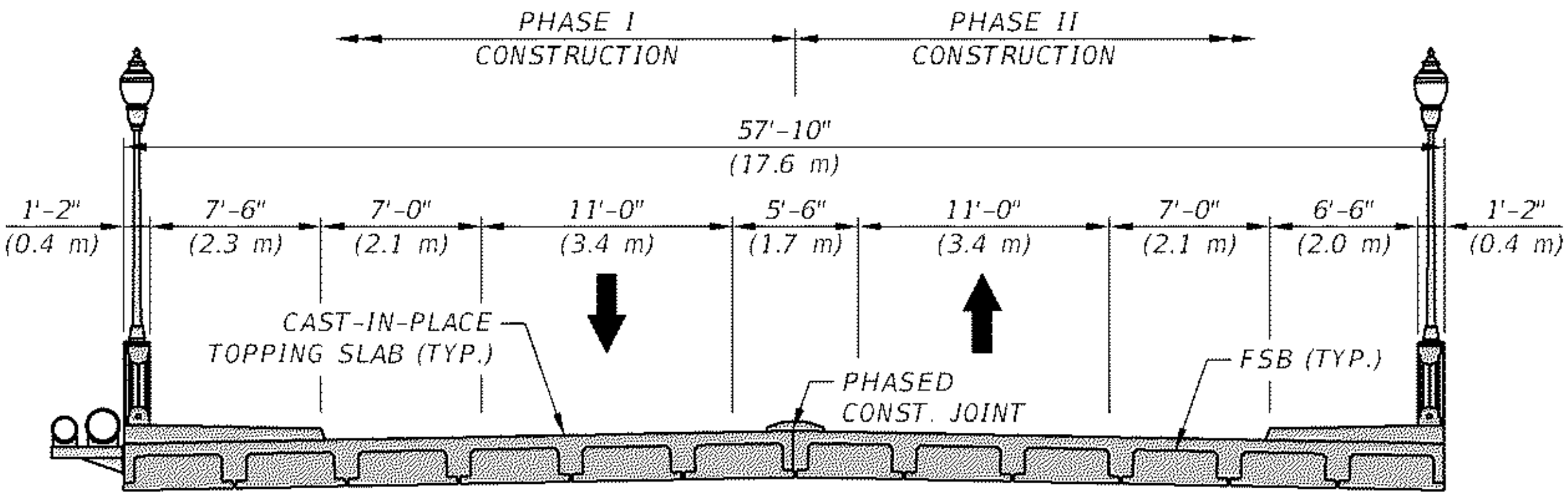
Design Approach

> Superstructure Design

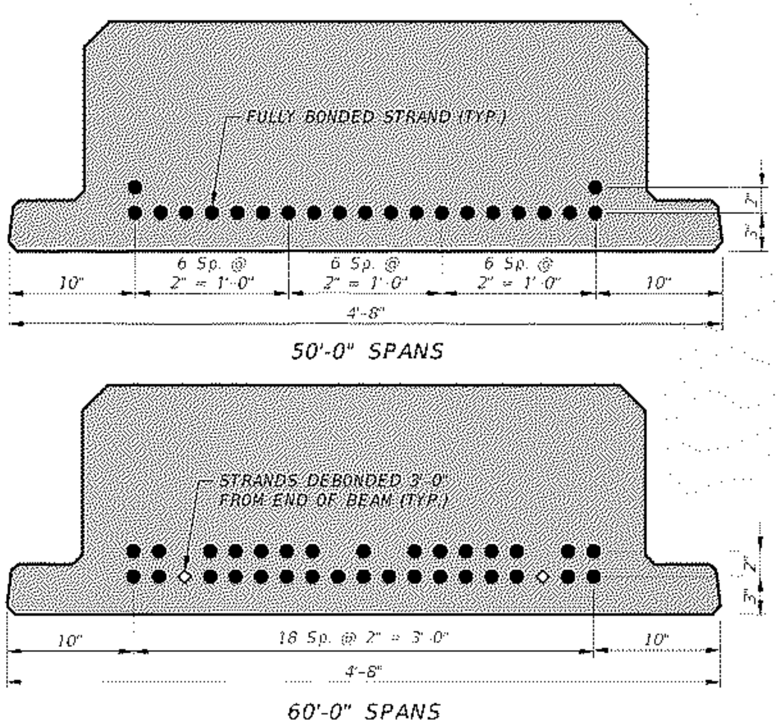
– Consisted of 4 – 50 ft (15.2 m) spans and 2 – 60 ft (18.3 m) spans

– 18 in (457 mm) deep FSB's with a 6 in (152 mm) cast-in-place topping slab

– Link slabs were utilized in the topping slab over the intermediate bents



Design Approach



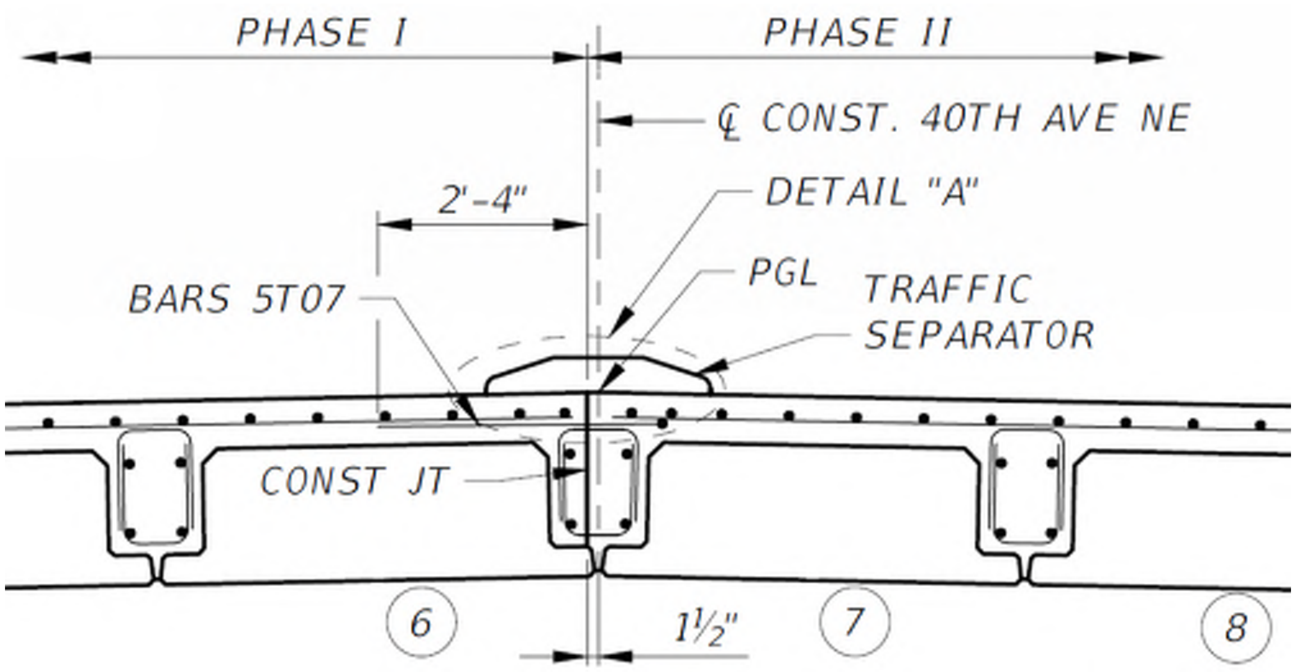
> Superstructure Design

- FSB's Utilized CFRP prestressing tendons with GFRP reinforcing bars
  - Concrete has 28-day compressive stress of 8,500 psi (59 MPa)
  - Tendons are 0.6 in (15 mm) diameter 7-strand
  - Tendons stressed to 70% of guaranteed ultimate tensile strength
- Topping slab utilized GFRP reinforcing bars
  - Concrete has a 28-day compressive stress of 5,500 psi (38 MPa)
  - Concrete included shrinkage reducing admixtures
- Link slab utilized GFRP reinforcing bars
  - Concrete has a 28-day compressive stress of 5,500 psi (38 MPa)
  - Concrete included shrinkage reducing admixtures and polymeric fibers
  - Debonding was set at 5% of the adjacent span

Challenges

> Phased Construction
  - Substructure construction joints required threaded mechanical splices that aren't available with GFRP reinforcing bars
  - Stainless steel reinforcing bars were lap spliced with GFRP bars to incorporate the threaded mechanical splices
  - Superstructure construction joint was aligned with a joint between FSB's and formed with the topping slab

> Cost Estimate
  - Accurate pricing without a developed history from previous projects



Next Steps

- Advertisement
  - Project was advertised in August 2020 with bids opened in September 2020
  - Bid prices for FRP elements

Item Description	Low Bid Unit Price	Ave. Unit Price
Fiber Reinforced Polymer Bars, #5 Bar	$1.75/LF	$2.37/LF
Fiber Reinforced Polymer Bars, #6 Bar	$2.71/LF	$2.85/LF
Fiber Reinforced Polymer Bars, #7 Bar	$3.44/LF	$3.24/LF
Fiber Reinforced Polymer Bars, #8 Bar	$3.74/LF	$3.37/LF
Prestressed Beam: Florida Slab Beam, Beam Depth 18"	$670/LF	$554/LF
Prestressed Conc Piling, 24" SQ w/FRP or SS Strand and Reinf	$378/LF	$561/LF

- Construction
  - Scheduled to start this winter

QUESTIONS?

Thank you

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75
YEARS
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Field Applications of Non-Conventional Reinforcing and Strengthening Methods for Bridges and Structures, Part 3 of 3

Moderator: Steven Nolan (Jimmy Kim & Antonio Nanni support)

6 x 16 min. presentations + 3 min. Q&A each.

1:05 pm **Repair of Structures Using UHPC**
Peter Weber *(ceEntek Pte Ltd)*

1:24 pm **Impact Damage Retrofit of RC Bridge Girder Previously Retrofitted with CFRP Fabric** - Issam Harik *(University of Kentucky)*

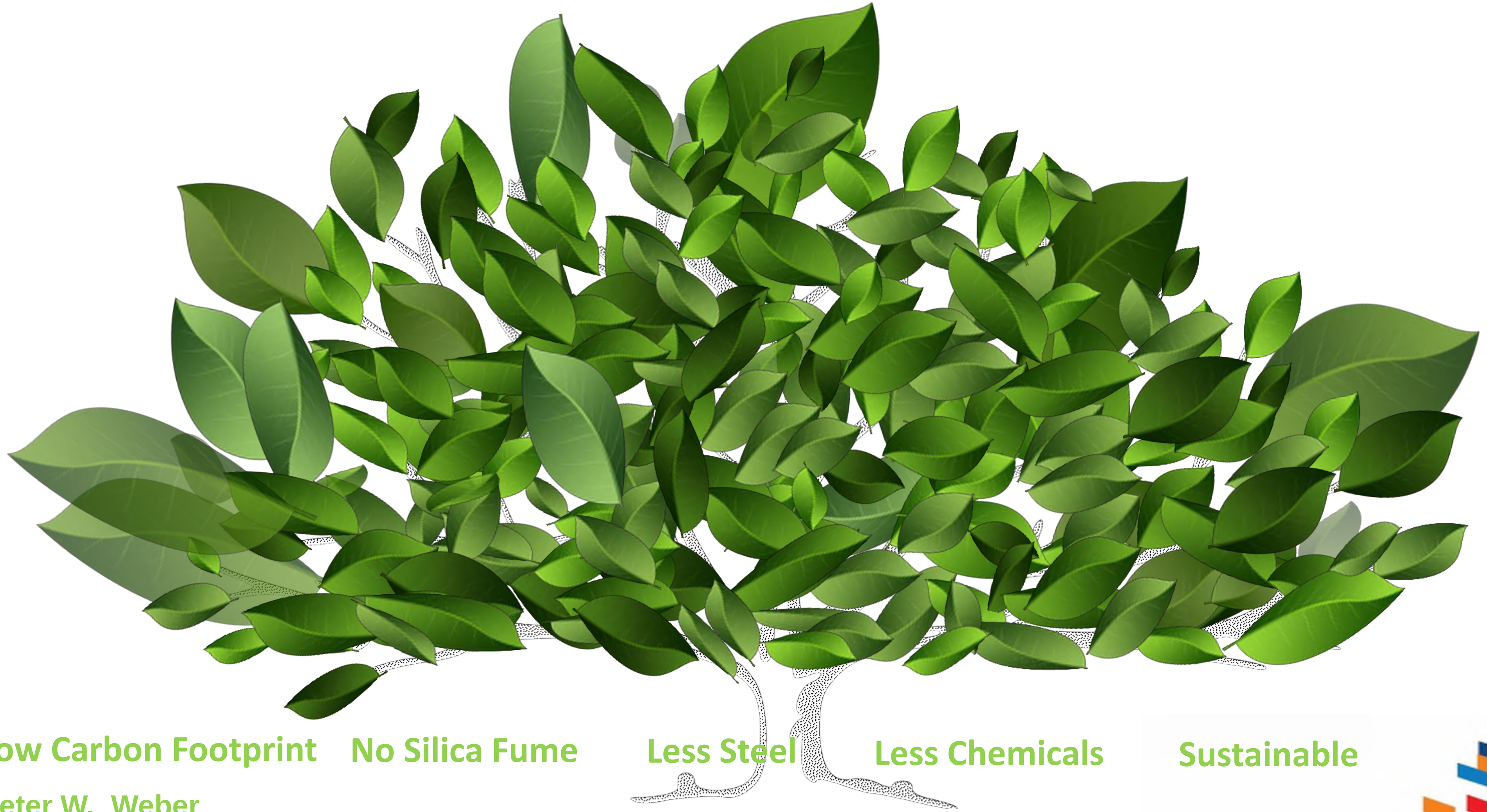
1:43pm **FRP Strengthening and Evaluation for Corrosion Deteriorated Bridge Bent Caps on US-80 Bridge near Dallas, TX**
Nur Yazdani *(University of Texas at Arlington)*

2:02 pm **FRP Retrofitting and Non-Destructive Evaluation for Corrosion-Deteriorated Bridges in West Virginia -** Hai Nguyen & Hien Nghiem *(Marshall University)*

2:21 pm **Bridge Substructure Repairs with Basalt, Carbon, and Glass FRP Internal Reinforcement -** Mohit Soni *(Stantec)*

2:40 pm **Shear Strengthening Sunshine Skyway Trestle Spans Beam Strengthening with CFRP -** Atiq Alvi *(T.Y. Lin International)*

Application of UHPC 2.0™ for a non-conventional reinforcing and strengthening of a reinforced concrete beam for bridges and structures



Less Cement | Low Carbon Footprint | No Silica Fume | Less Steel | Less Chemicals | Sustainable

Wang Su, PhD, Peter W. Weber
ceEntek Pte Ltd

BUILDING A LASTING FUTURE

A new concept for bridge and raised roadway repair and strengthening

Courtesy Walo Switzerland

Bridge Overlay: Strengthen, Repair and Protect the Bridge Structure

Initial focus on Market in Switzerland and NA in cooperation with local contractors

- Advanced concept for Bridge rehabilitation
  - No added weight to the structure
  - Strengthening plus protection
  - Stops Chloride penetration into the structure
  - Extended lifetime

- On the way to worldwide standard
  - Switzerland, USA, China
- Requires thixotropic UHPC
- Critical material issues
  - Consistent fresh properties
  - Consistent hardened properties
  - Bond strength
  - Cost

- Worldwide opportunities
  - USA, Europe, China
  - Requires trained local contractor

Newport Bridge, Rhode Island, October 2020, ceEntek ce200SF-t

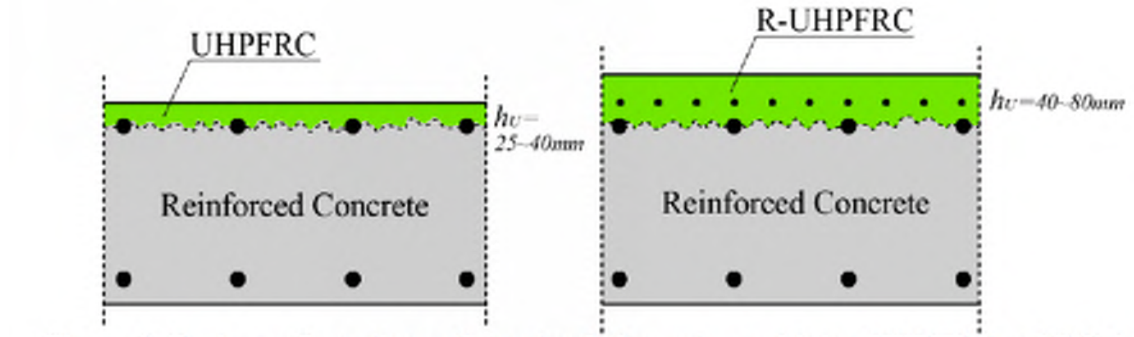
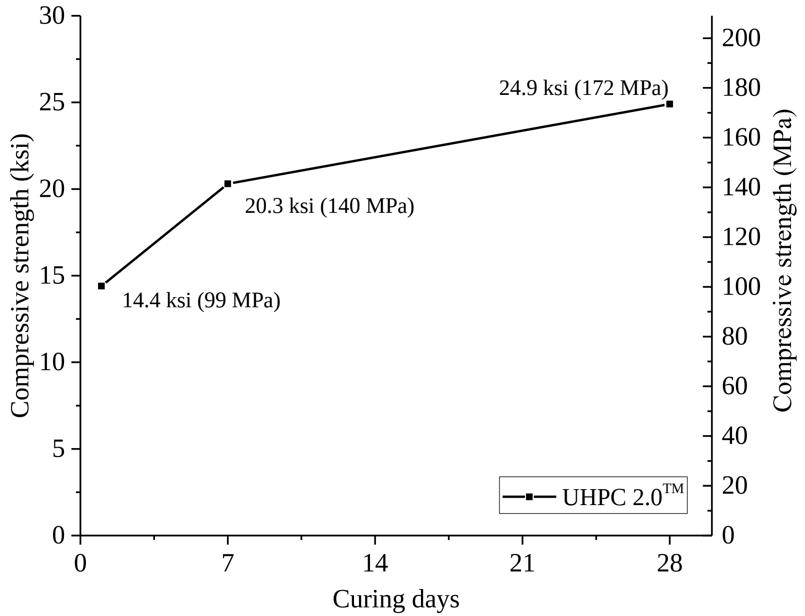


Figure 3: Basic configurations of structural elements combining UHPFRC and RC: left: UHPFRC layer has a protective function only; right: R-UHPFRC layer has structural resistance and protective functions.

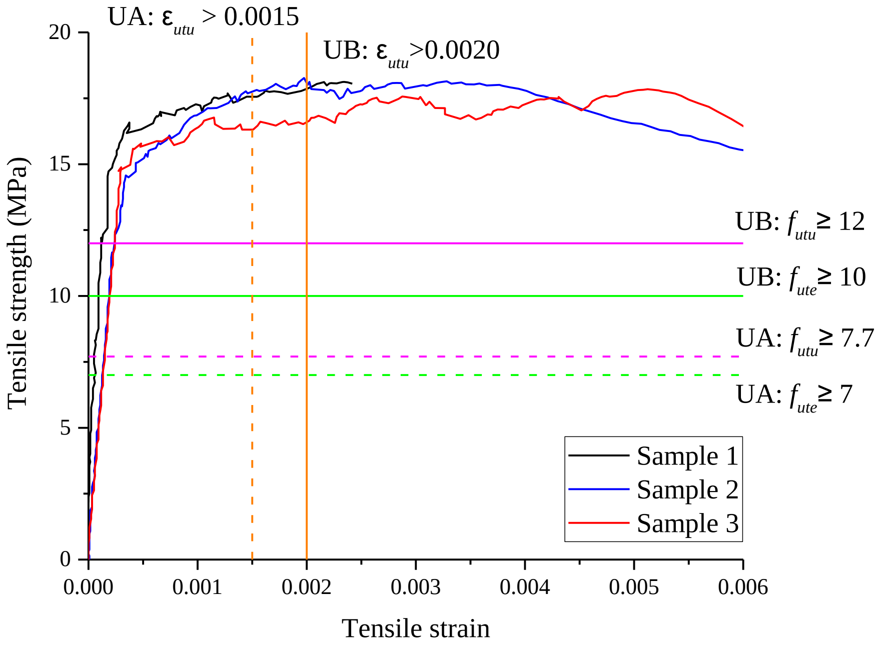
Fresh properties of ce200SF-t™: Thixotropic behavior

ceEntek Solution For Bridge Overlay: UHPC 2.0™ (ce200SF-t™)

Compressive strength of ce200SF-t™



Direct tensile performance of ce200SF-t™



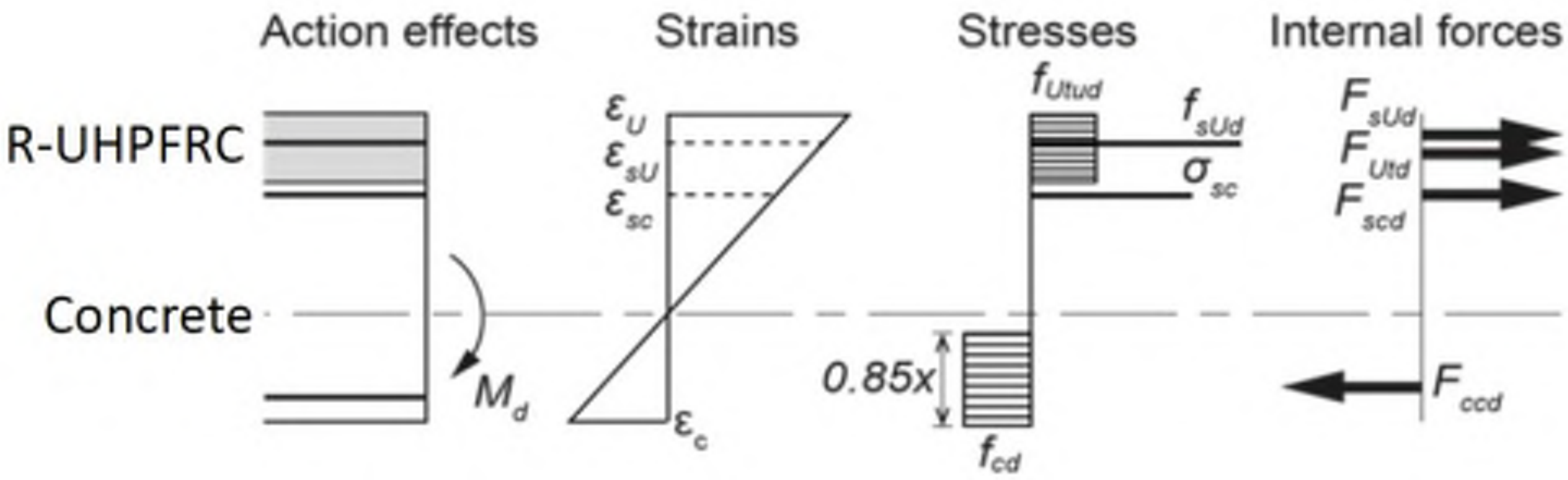
Flexural strength and elastic modulus of ce200SF-t™

Curing ages	7 days	28 days
Flexural strength (ksi/MPa)	6.1/42.0	7.6/52.2
Elastic modulus (ksi/GPa)	5613/38.7	7470/51.5

Comparison of the requirements of SIA 2052 with measured values in the direct tensile test

Parameter	Required minimum value			Measured values			Requirements for		
	UO	UA	UB	Sample 1	Sample 2	Sample 3	UO	UA	UB
f_{ute}, ksi (MPa)	≥ 1.0 (7.0)	≥ 1.0 (7.0)	≥ 1.5 (10.0)	2.1 (14.3)	2.1 (14.3)	2.1 (14.7)	Fulfilled	Fulfilled	Fulfilled
f_{utu} ksi (MPa)	≥ 0.7 (4.9)	≥ 1.1 (7.7)	≥ 1.7 (12)	2.6 (18.1)	2.7 (18.3)	2.6 (17.8)	Fulfilled	Fulfilled	Fulfilled
f_{utu}/f_{ute}	> 0.7	> 1.1	> 1.2	1.27	1.28	1.21	Fulfilled	Fulfilled	Fulfilled
ε_{utu} (%)	-	> 0.15	> 0.2	0.23	0.21	0.51	Fulfilled	Fulfilled	Fulfilled

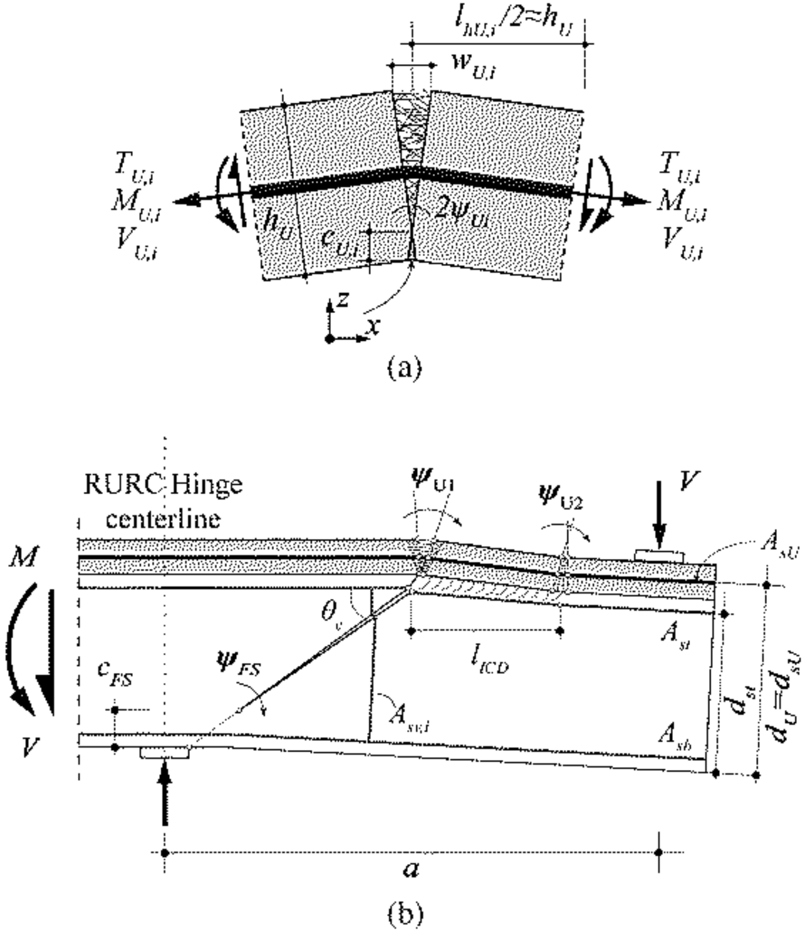
Mechanism of bending resistance of UHPFRC reinforced concrete beam (RU-RC beam) [1]



Tensile strength is primary force

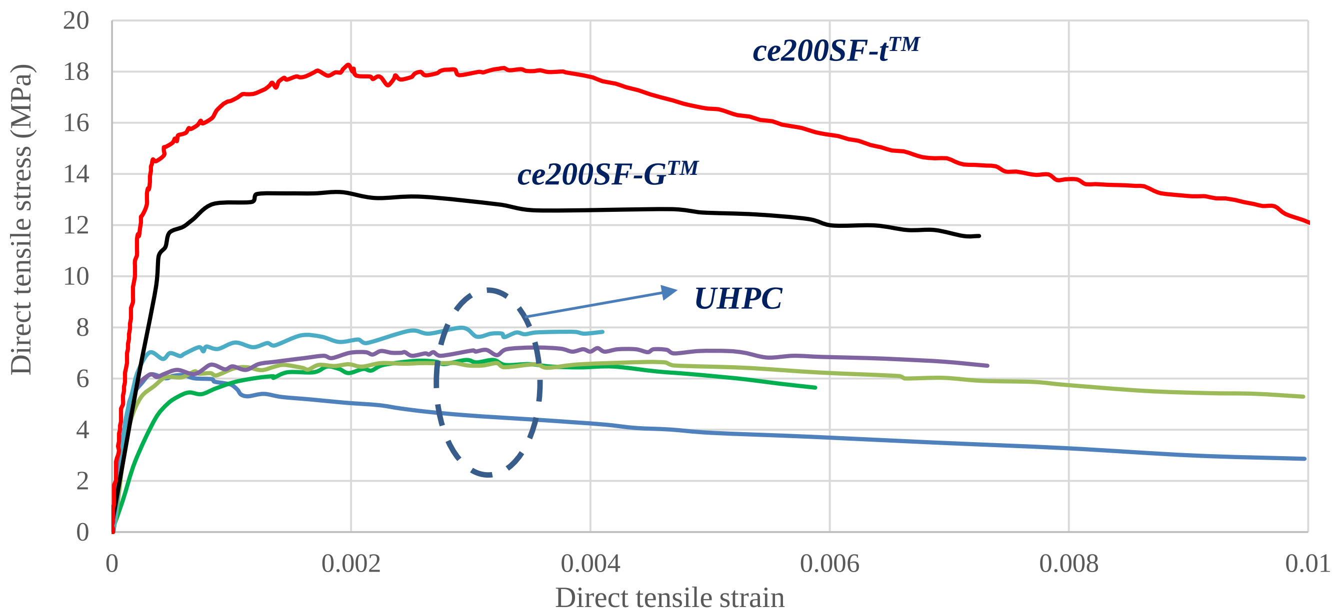
ceEntek Solution For Bridge Overlay: UHPC 2.0™ (ce200SF-t™)

Importance of tensile strength



Flexural- Shear collapse mechanism (a) R-UHPFRC hinge;
(b) flexure-shear crack defining the member failure [2]

ceEntek UHPC 2.0™ VS UHPC in tensile performance



Balance of Bonding-, Compression- and Tensile strength

- Bonding strength defines monolithic behavior
- Compression- plus tensile strength define the member failure

ceEntek Solution For Bridge Overlay: UHPC 2.0™ (ce200SF-t™)

Rapid chloride penetration test (ASTM C1202)

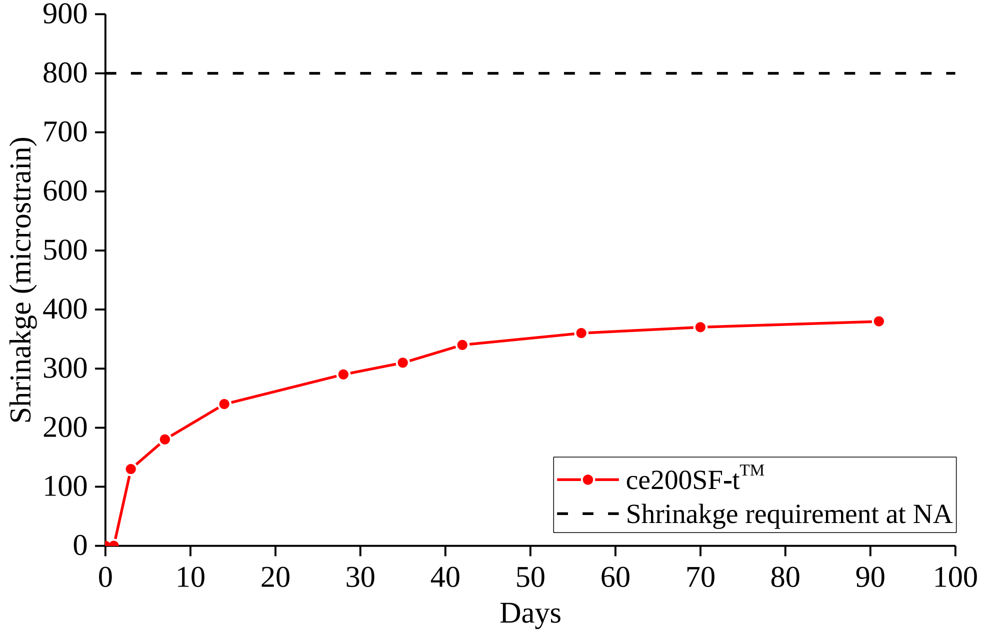
	Sample 1	Sample 2	Sample 3	Average	Classification
Charge passed (coulumbs)	205	186	211	200	Very low

Water absorption test (ASTM C642)

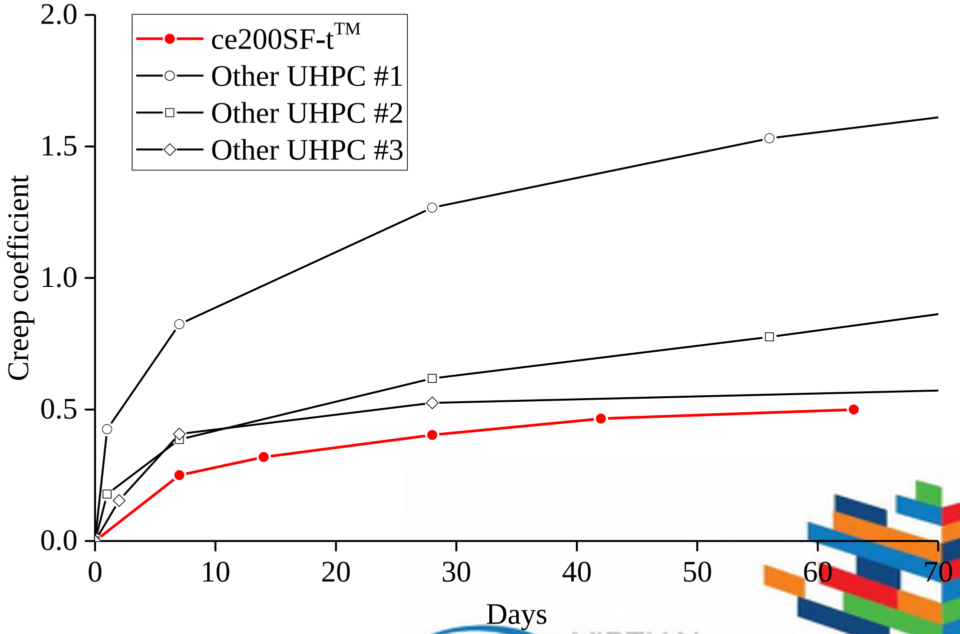
	Sample 1	Sample 2	Average	Classification
Absorption after immersion %	0.7	0.65	0.675	DL200*

*DL200 is the top classification in Canada standard --- CSA A23.1-19 Annex U

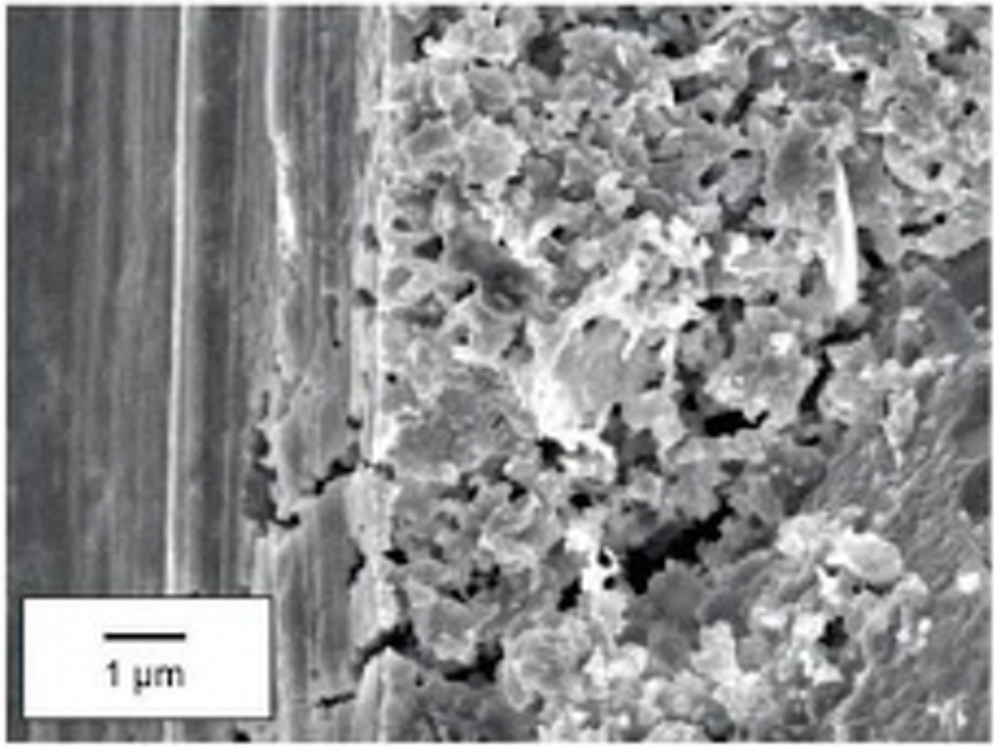
Drying shrinkage test (SIA 262/1, appendix F)



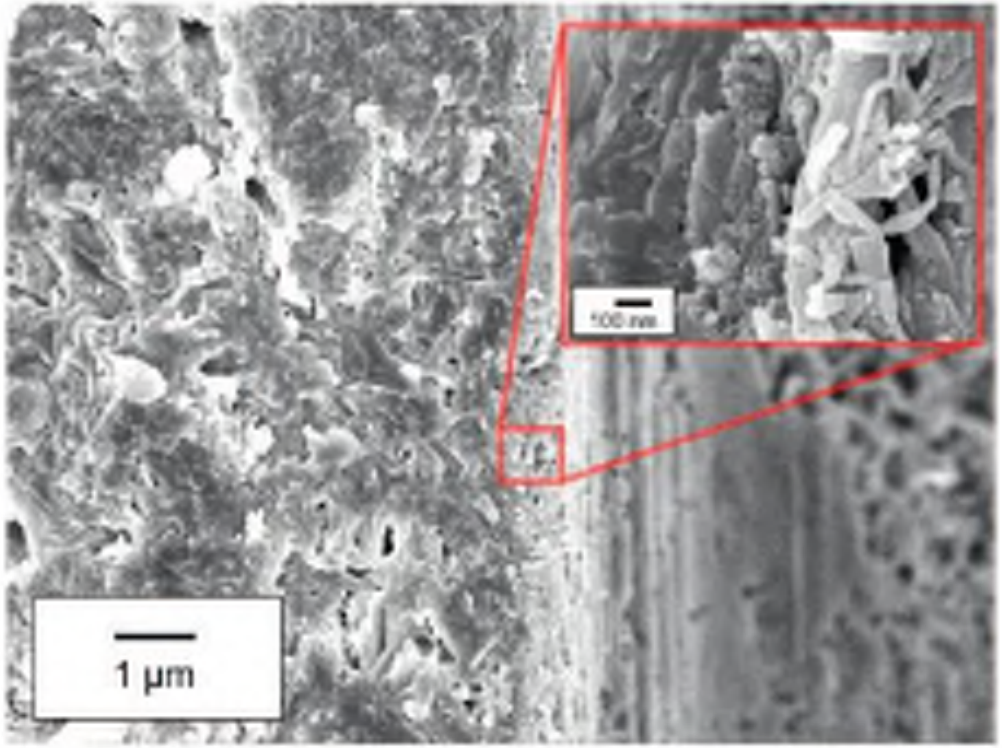
Creep test (SIA 262/1, appendix F)



Advantage of Nano-technology



Porous interfacial transition zone between fiber and UHPC [3]



Denser interfacial transition zone between fiber and ceEntek UHPC 2.0™ [3]

‘Wall’ effect creates Nanofibers rich transition Zone around Macro-fibers

ceEntek Solution For Bridge Overlay: UHPC 2.0™ (ce200SF-t™)

Certification tests of ce200SF-t™, SIA2052, Switzerland

Switzerland is one of the first countries worldwide with a Code for UHPC.

SIA2052 specifies three different levels of performance: UO, UA and UB (highest)

ceEntek is meeting and exceeding the highest levels of requirement as specified in the Code.

While worldwide Codes may differ slightly, UHPC is on the way to become a standardized product.

parameter	required miminum value			measured value		requirements for		
	UO	UA	UB	tensile test	flexural test	UO	UA	UB
f_{Utek} f_{Utuk} / f_{Utek} ε_{Utu}	≥ 7.0 MPa > 0.7 -	≥ 7.0 MPa > 1.1 > 1.5 ‰	≥ 10.0 MPa > 1.2 > 2.0 ‰	13.0 MPa 1.23 3.15 ‰	10.8 MPa 1.45 3.62 ‰	fulfilled fulfilled fulfilled	fulfilled fulfilled fulfilled	fulfilled fulfilled fulfilled
strength	f_{Uck} ≥ 120 MPa			158.7 MPa		fulfilled		

parameter	required miminum value			measured value	requirements for		
	UO	UA	UB		UO	UA	UB
compressive strength	f_{Uck} ≥ 120 MPa			163.7 MPa	fulfilled		
sorption coefficient	S < 100 $g/(m^2 \cdot h^{0.5})$			89.0 $g/(m^2 \cdot h^{0.5})$	fulfilled		

parameter	measured value
Elastic modulus after 28 days, SN EN 12390-13, prisms 40x40x160 mm	51.5 GPa
Shrinkage value after 91 days, SIA 262/1, appendix F, sealed prisms 40x40x160 mm	- 0.28 ‰
Shrinkage value after 91 days, SIA 262/1, appendix F, unsealed prisms 40x40x160 mm	- 0.38 ‰
Autogenous shrinkage, ASTM-C 1698-09, up to 28 days	- 0.59 ‰
Creep coefficient after 91 days, SIA 262/1, appendix F, unsealed prisms 40x40x160 mm	0.50

Calculation of Bending Resistance Of UHPFRC Reinforced Concrete Beam (RU-RC Beam)

The bending resistance calculated here is at a negative bending moment cross section where the UHPFRC layer is in tension and the bottom of the original concrete beam is in compression. At the ultimate limit state, the bottom surface of the original concrete beam is crushed, in other word, the concrete strain at bottom surface reach the ultimate value $\boldsymbol{\varepsilon_c = 0.003}$. At them same time, for a tension failure mode, the steel reinforcement in the UHPFRC layer is yielding. According on the calculation graph in last slide and force equilibrium, the depth of compressive zone $\boldsymbol{x}$ can be calculated according to following equations:

$$f_{Utu} b h_u + f_{sU} A_{sU} + \sigma_{sc} A_{sc} = 0.85x \cdot f_{cd} b$$

$$\sigma_{sc} = E_{sc} \varepsilon_c \cdot \frac{d_{sc} - x}{x}$$

If $\sigma_{sc} < f_{sc}$, then the bending resistance M is:

$$M = f_{Utu} b h_u (h_c + h_U - 0.425x - \frac{h_U}{2}) + f_{sU} A_{sU} (d_{sU} - 0.425x) + \sigma_{sc} A_{sc} (d_{sc} - 0.425x)$$

If $\sigma_{sc} \geq f_{sc}$, then the depth of compressive zone x should be re-calculated:

$$x = (f_{Utu} b h_u + f_{sU} A_{sU} + f_{sc} A_{sc}) / (0.85 f_{cd} b)$$

Then the bending resistance M should be calculated by the last equation again.

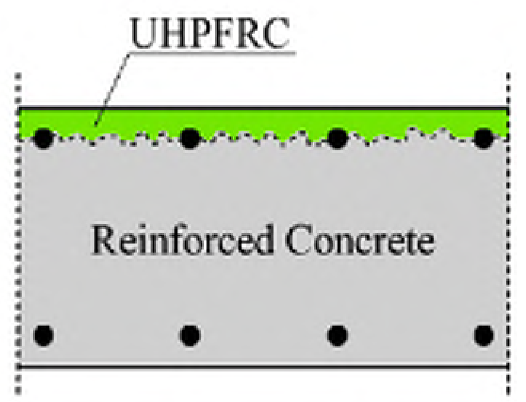
b is the width of the beam cross section; h_c is the height of the beam cross section; h_U is the thickness of UHPFRC layer; $d_{sU}$is the distance between the steel reinforcement at UHPFRC layer and bottom surface of the original concrete beam; f_{sU} is the yield strength of steel bars at UHPFRC layer; A_{sU} is the steel bar area at UHPFRC layer; σ_{sc} is the tension stress at the top steel reinforcement of the original concrete beam;f_{sc} is the yield strength of the top steel reinforcement of the original concrete beam;E_{sc} is the elastic modulus of the top steel reinforcement of the original concrete beam; $d_{sc}$is the distance between the top steel reinforcement and bottom surface of the original concrete beam; A_{sc} is the steel bar area of the top steel reinforcement of the original concrete beam; f_{cd} is the compressive strength of original concrete;

Application of UHPC 2.0™ (ce200SF-t™) In Beam Repairing

ce200SF-t™ displays a higher tensile strength than traditional UHPFRC

	f_{Utu} (MPa)
ce200SF-t™	18
Traditional UHPFRC	10

Case 1 : repairing overlay without steel reinforcement



	b (mm)	h (mm)	f_c (MPa)	f_{sc} (MPa)	ρ_{sc} (%)	f_{Utu} (MPa)	h_U (mm)
Traditional UHPFRC	150	250	50	566	0.66	10	**50**
ce200SF-t™						18	**26**

To obtain the same reinforcement strength, the layer of **ce200SF-t™** needed is significantly lower than with traditional UHPFRC: with an **overlay 48% thinner**, the same results can be achieved.

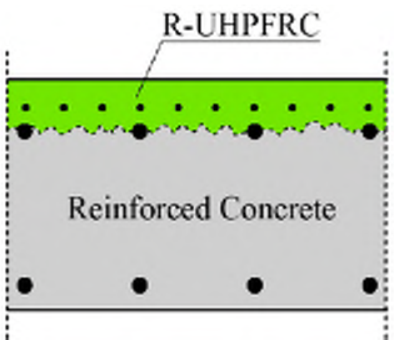
b is the width of the beam cross section; **h** is the height of the beam cross section; f_c is the compressive strength of original concrete; f_{sc} is the yield strength of the top steel reinforcement of the original concrete beam; ρ_{sc} is the ratio of the bottom steel reinforcement area over the effective depth of the beam cross section; f_{Utu} is the UHPFRC tensile strength; h_U is the thickness of UHPFRC layer.

Application of UHPC 2.0™ (ce200SF-t™) In Beam Repairing

ce200SF-t™ displays a higher tensile strength than traditional UHPFRC

	f_{Utu} (MPa)
ce200SF-t™	18
Traditional UHPFRC	10

Case 2 : repairing overlay with steel reinforcement



	b (mm)	h (mm)	f_c (MPa)	f_{sc} (MPa)	ρ_{sc} (%)	f_{sU} (MPa)	ρ_{sU} (%)	f_{Utu} (MPa)	h_U (mm)
Traditional UHPFRC	150	250	50	566	0.66	710	2.70	10	**50**
ce200SF-t™								18	**29**

With a steel-reinforced UHPFRC layer, to obtain the same reinforcement strength, the layer of **ce200SF-t™** needed is significantly lower than with traditional UHPFRC: with an **overlay 42% thinner**, the same result can be achieved.

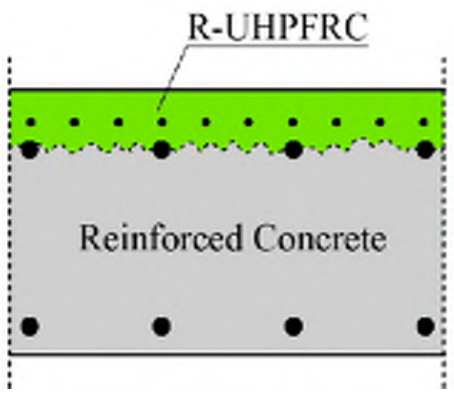
b is the width of the beam cross section; **h** is the height of the beam cross section; f_c is the compressive strength of original concrete; f_{sc} is the yield strength of the top steel reinforcement of the original concrete beam; ρ_{sc} is the ratio of the bottom steel reinforcement area over the effective depth of the beam cross section; ; f_{sU} is the yield strength of steel bars at UHPFRC layer; ρ_{sU} is the steel bar ratio at UHPFRC layer; f_{Utu} is the UHPFRC tensile strength; h_U is the thickness of UHPFRC layer.

Application of UHPC 2.0™ (ce200SF-t™) In Beam Repairing

ce200SF-t™ displays a higher tensile strength than traditional UHPFRC

	f_{Utu} (MPa)
ce200SF-t™	18
Traditional UHPFRC	10

Case 3 : repairing overlay with steel reinforcement, keeping the same layer thickness, but reducing the steel reinforcement volume



	b (mm)	h (mm)	f_c (MPa)	f_{sc} (MPa)	ρ_{sc} (%)	f_{sU} (MPa)	h_U (mm)	f_{Utu} (MPa)	ρ_{sU} (%)
Traditional UHPFRC	150	250	50	566	0.66	710	50	10	**2.70**
ce200SF-t™								18	**1.56**

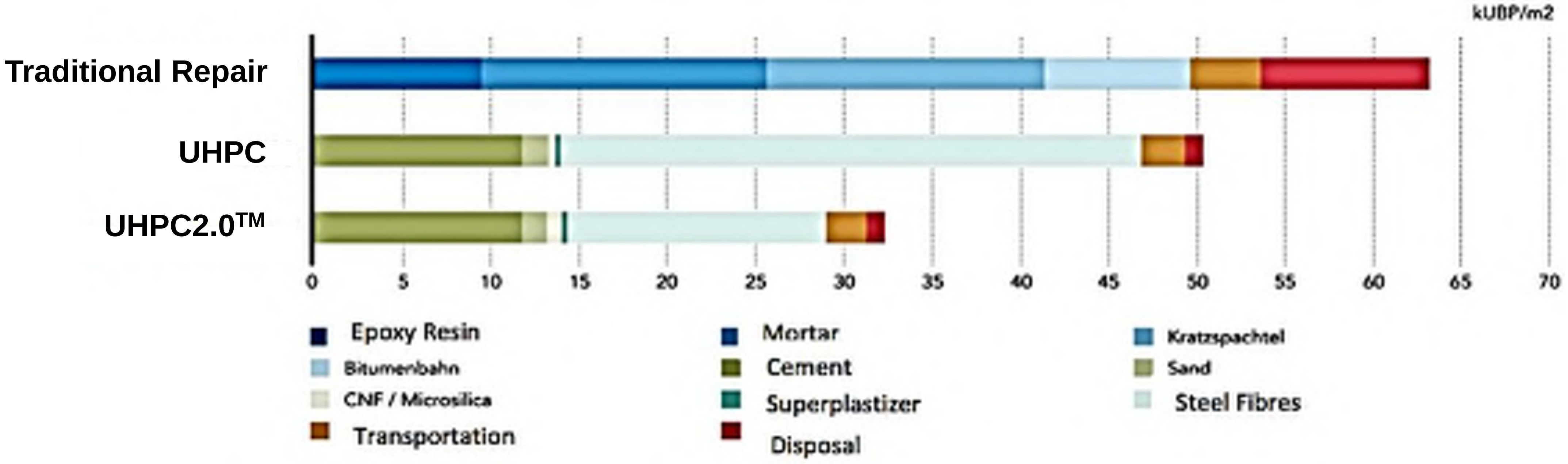
With a steel-reinforced UHPFRC overlay, with a same layer thickness (50 mm), the amount of steel bar reinforcement needed with **ce200SF-t™** is significantly lower than with traditional UHPFRC: with **a reduction of 42% in steel bar volume**, the same result can be achieved.

b is the width of the beam cross section; **h** is the height of the beam cross section; f_c is the compressive strength of original concrete; f_{sc} is the yield strength of the top steel reinforcement of the original concrete beam; ρ_{sc} is the ratio of the bottom steel reinforcement area over the effective depth of the beam cross section; ; f_{sU} is the yield strength of steel bars at UHPFRC layer; h_U is the thickness of UHPFRC layer; f_{Utu} is the UHPFRC tensile strength; ρ_{sU} is the steel bar ratio at UHPFRC layer.

Advantages of applying UHPC 2.0™ (ce200SF-t™) In Bridge Repairing

Carbon Footprint of ce200SF-t™ evaluated by Carbotech, Switzerland for Swiss Railway (SBB)

Results for Environmental Footprint: Detailed Comparison in kUBP, per m²



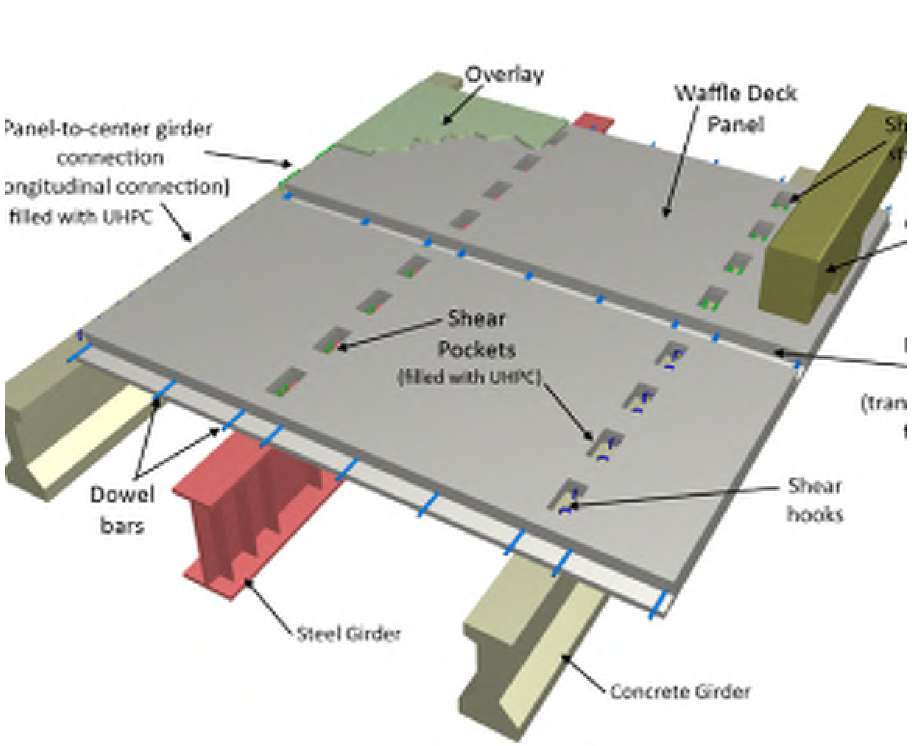
Impact of steel fibers to the carbon footprint of UHPC*

* Same level of flexural strength

EXAMPLE: UHPC2.0^{TM} BRIDGE DECKS

Ultra-high-performance concrete (UHPC) is rapidly emerging as a premier material for precast concrete construction and is ready to revolutionise and potentially change building and bridge design

Efficient use of materials, improved space utilization, better logistics.



a) Schematic showing components a bridge with precast UHPC waffle deck system

UHPC based 'waffle decks' are lighter and easier to handle and transport than traditional concrete decks. This will reduce amount of concrete and logistic cost

When comparing a conventional concrete slab bridge deck used for 40- to 60-ft spans in accelerated bridge construction (ABC) applications and an optimized UHPC voided box slab using the same depth, width and load capacity, the UHPC product has about:

- **52%** of the concrete
- Less than **4%** of the steel
- **50%** increased delivery radius

Source: https://www.enr.com/articles/49236-ultra-high-performance-concrete-is-ready-to-revolutionize-precast-prestressed-concrete

REFERENCE

[1] Bastien-Masse, M., & Brühwiler, E. (2016). Contribution of R-UHPFRC strengthening layers to the shear resistance of RC elements. *Structural Engineering International*, *26*(4), 365-374.

[2] Noshiravani, T., & Brühwiler, E. (2014). Analytical model for predicting response and flexure-shear resistance of composite beams combining reinforced ultrahigh performance fiber-reinforced concrete and reinforced concrete. Journal of Structural Engineering, 140(6), 04014012.

[3] He, S., Qiu, J., Li, J., & Yang, E. H. (2017). Strain hardening ultra-high performance concrete (SHUHPC) incorporating CNF-coated polyethylene fibers. *Cement and concrete research*, *98*, 50-60.

BUILDING A LASTING FUTURE

Impact Damage Retrofit of RC Bridge Girder Previously Retrofitted with CFRP Fabric

Abheetha Peiris and Issam Harik

University of Kentucky

aci CONCRETE CONVENTION

1

Outline

- Introduction

- 2015 Repair of KY 562 Over I-71
- 2018 Repair of KY 562 Over I-71
- Conclusions
- Acknowledgment

2

KY Bridge Repair With FRP

- 42 by Harik's Team
- 10 due to Truck Impact

3

Truck-Bridge Impact – Repair With CFRP

4

Outline

- Introduction

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Glass Fiber Mesh

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Glass Fiber Mesh Damaged in July 2014

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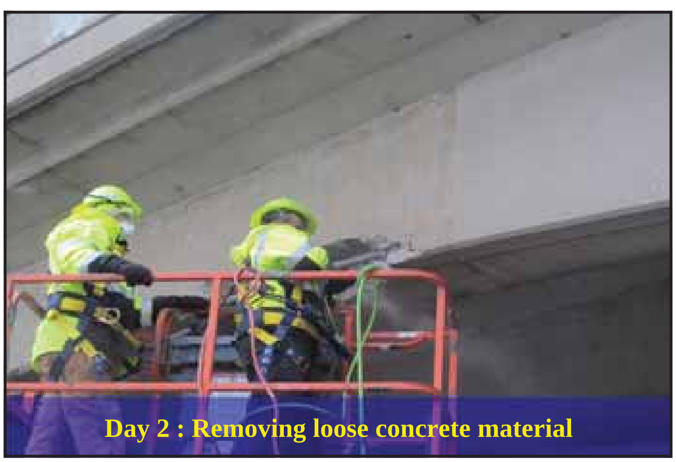
Day 1 : Removal of Glass Fiber Mesh

9

Day 1 : Cutting off bent rebar

10



Day 2 : Removing loose concrete material

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Day 2 : Sand blasting

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Day 2 : Replacing cut rebar

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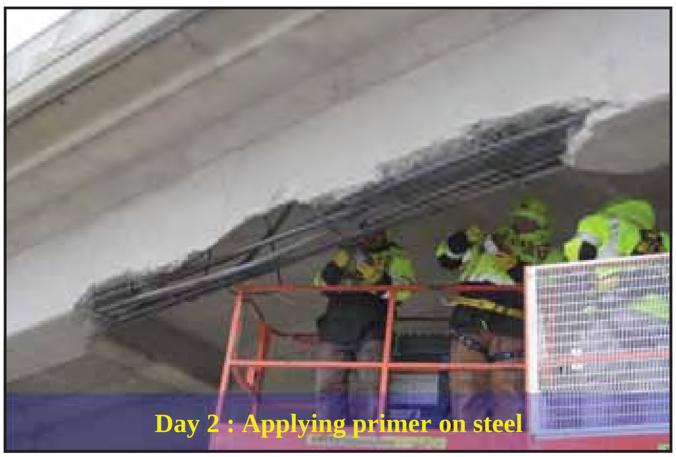
Day 2 : Tightening coupler

14


Day 2 : Applying primer on steel

15


Day 7 : Mixing repair mortar with accelerant

16


Day 7 : Placement of repair mortar

17


Day 8: Grinding and finishing surface preparation

18

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Outline

- Introduction
- 2015 Repair of KY 562 Over I-71
- **2018 Repair of KY 562 Over I-71**
- Conclusions
- Acknowledgment

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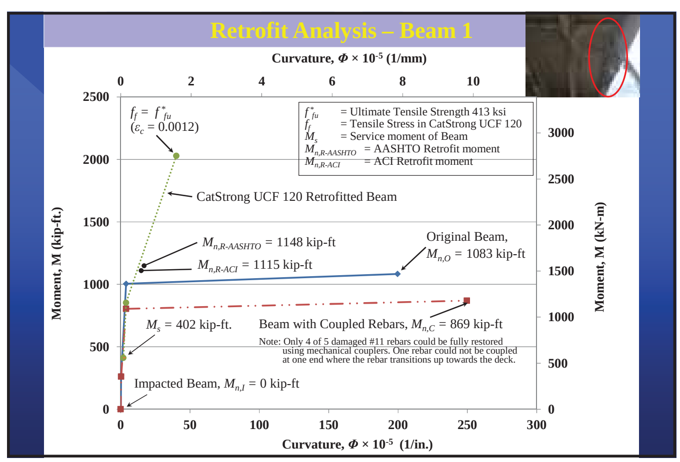

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Retrofit Analysis - 039B00017N

Beam Condition	Moment Capacity (kip-ft)	
	Beam 1	Beam 2
As-Built Beam	1083	1083
Beam Impacted on 09/09/2018	0	976
Beam Retrofitted on 11/08/2018	1148	1253

Note: Bridge load rating and posting prior to impact on 09/06/2018 can be maintained.

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Outline

- Introduction
- 2015 Repair of KY 562 Over I-71
- 2018 Repair of KY 562 Over I-71
- **Conclusions**
- Acknowledgment

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Conclusion

Structural concrete repair is an area where FRP Materials compete and win

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Outline

- Introduction
- 2015 Repair of KY 562 Over I-71
- 2018 Repair of KY 562 Over I-71
- Conclusions
- **Acknowledgment**

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Acknowledgment

- FRP Researchers, Guides & Codes
- Kentucky Transportation Cabinet
- Federal Highway Administration
- University of Kentucky
- Industry

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Questions?

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Evaluation of FRP Strengthening for Deteriorated Bridge Bent Caps

Nur Yazdani, Professor,
University of Texas at Arlington
Department of Civil Engineering

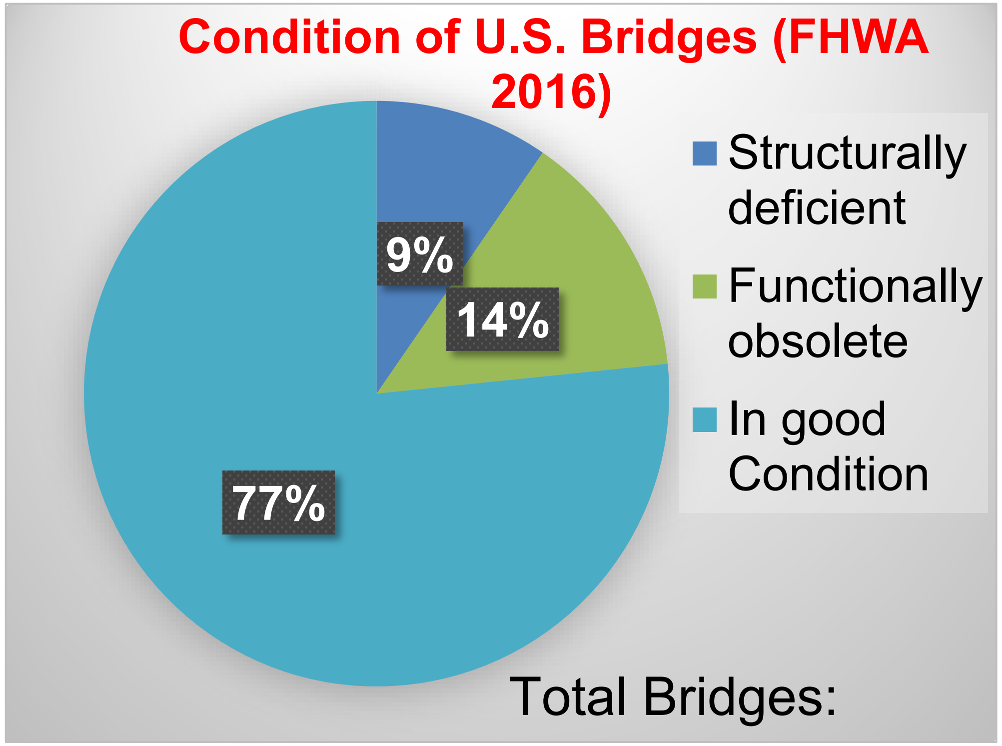
Yazan Almomani,
Assistant Professor, Univ. of Petra, Jordan

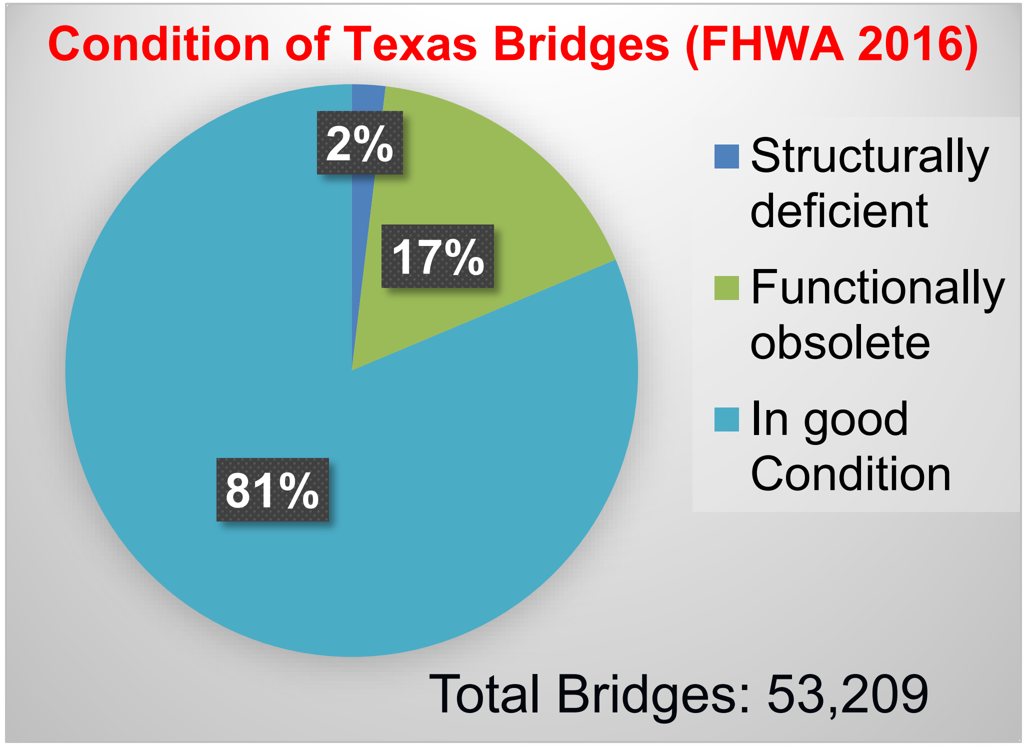
Presentation Outline

- Introduction
- Background
- Problem Statement
- Objectives
- Bridge Description
- Concrete Repair and CFRP Strengthening
- Non-Destructive Load Testing
- Numerical Modeling
- Conclusions

Introduction

- Almost 39% of U.S bridges are 50 years or older, and there were an average of 188 million trips across structurally deficient bridges each day (ASCE Report Card, 2017)





Source: Federal Highway Administration Annual Report, 2016

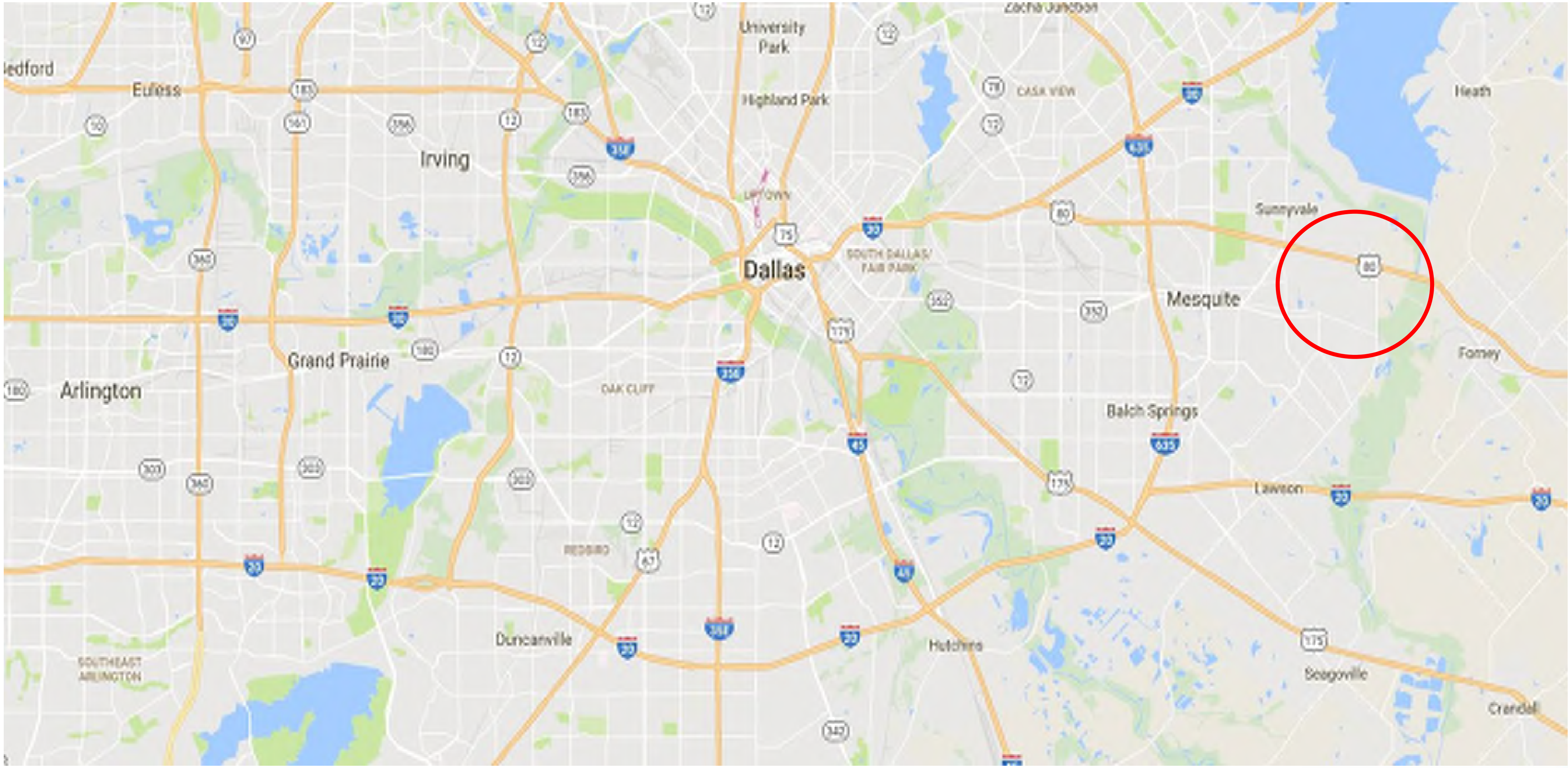
FRP Laminate Strengthening

- Widely used for bridge superstructure
- Less used for substructure

Bridge Description

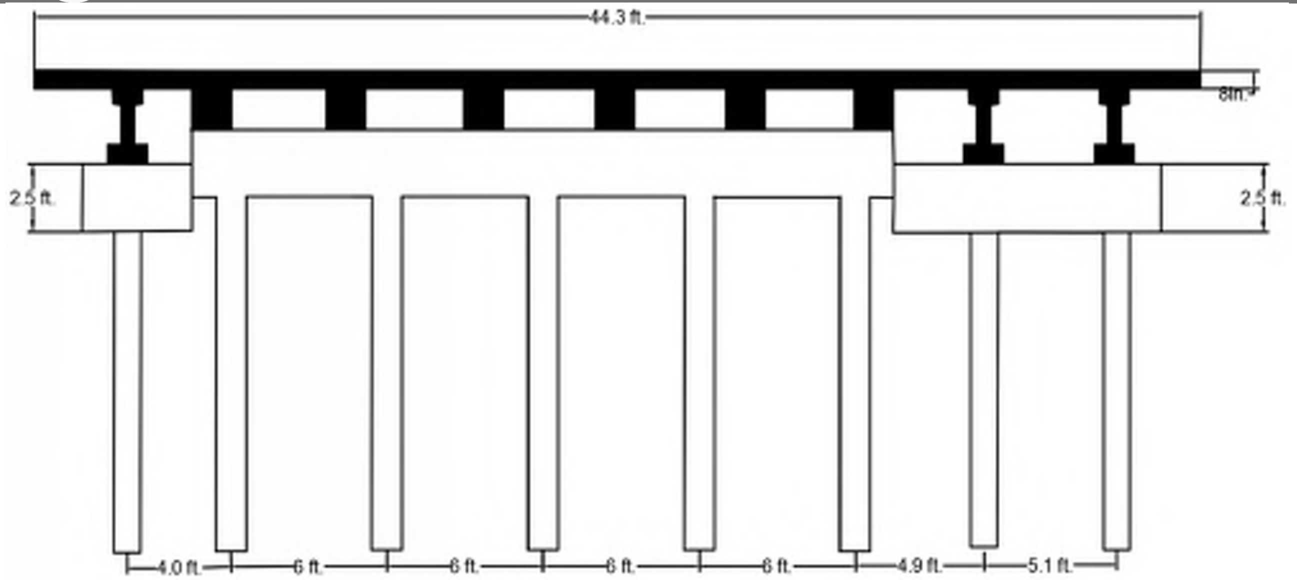
- The west bound of US 80 over East Fork Trinity River Bridge in Dallas, TX, was selected for this study
- Built in 1940 and widened in1970.
- Cast-in place reinforced concrete with 52-25 ft. spans.
- The average daily traffic is around 29,000 vehicles (NBI 2016)
- 8-in. composite deck.
- Total of 6 concrete T beams per span.

Location


University Park
Highland Park
Zacha Junction
CASA VIEW
Heath
Euless
Irving
Sunnyvale
UPTOWN
Dallas
SOUTH DALLAS/ FAIR PARK
Mesquite
Forney
Grand Prairie
Arlington
OAK CLIFF
Balch Springs
Lawson
REDBIRD
Duncanville
Hutchins
Seagoville
SOUTHEAST ARLINGTON
Crandall

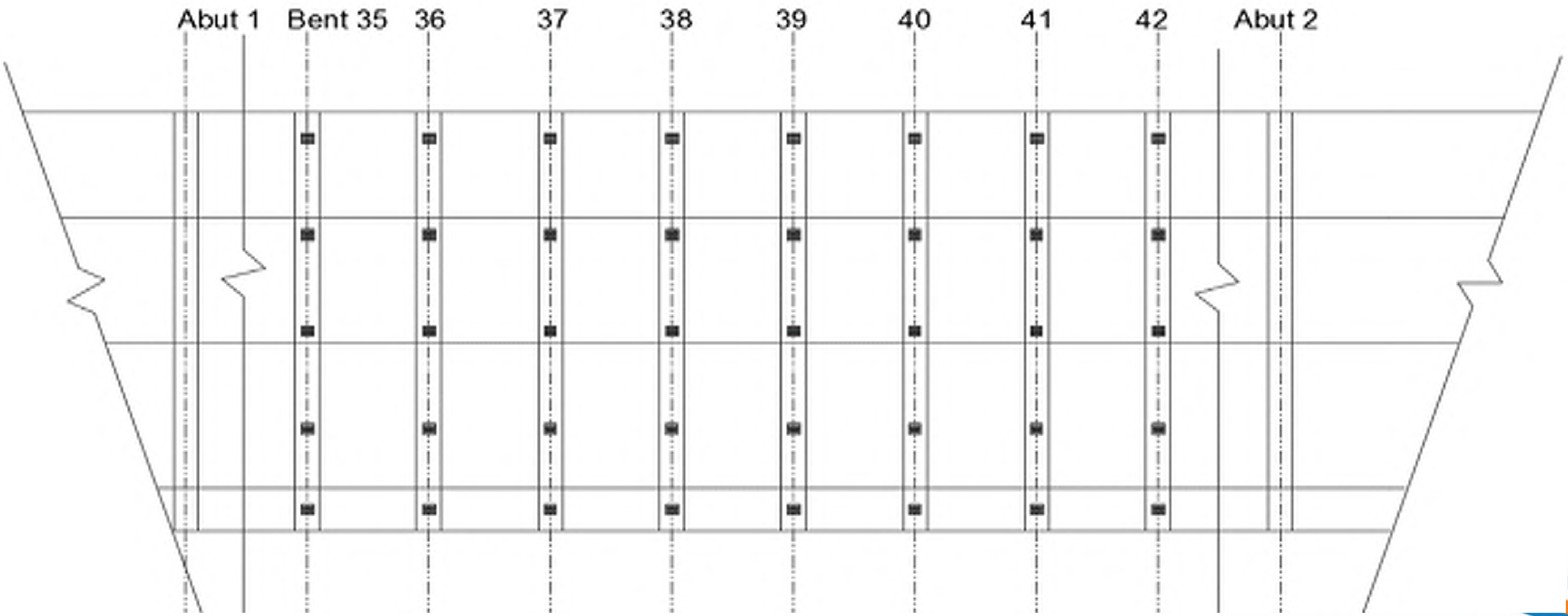
Background

- 41.5 ft. clear roadway width with 2-2 ft. traffic lanes.
- 2000 psi concrete compressive strength.
- 33 ksi reinforcing steel yield strength.
- Significant concrete damage in some bent caps.



Background

- Eight bent caps selected for repair.



Visual Inspection

- Significant concrete spalling.
- Flexural and shear rebars exposed in some spalled areas. Some excessive corrosion.
- Difficult access to underneath of the bridge.

Concrete Surface Preparation

CFRP Application

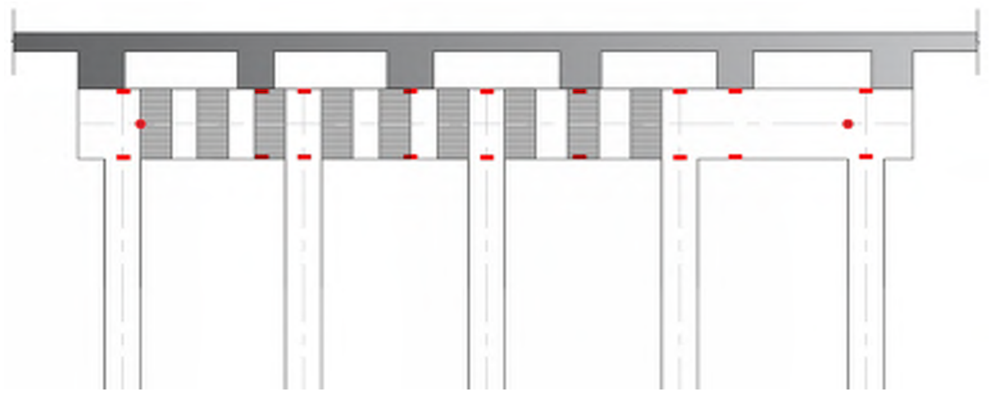
- The surface profile was prepared to CSP 3.
- CFRP was then applied on the repaired areas. For flexural strengthening, 24 in. wide CFRP used at bottom of the bent cap.

UNIVERSITY OF TEXAS

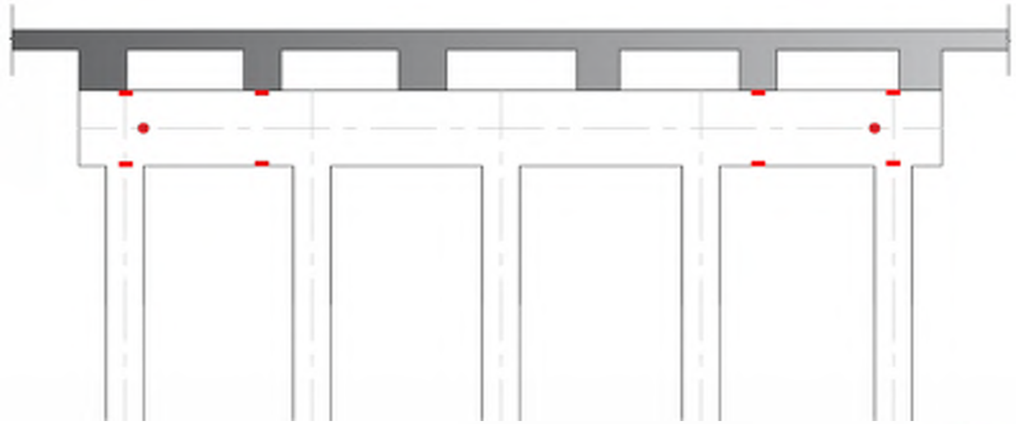
Instrumentation and Load Testing after Repair

- Instrumentation and load testing after repair was carried out in August 2017.
- A total of 38 concrete and FRP strain gages were installed.
- Fully loaded dump trucks used.
- AASHTO static and crawl speed tests used.

	Axle 1 weight (lb.)	Axle 2 weight (lb.)	Axle 3 weight (lb.)	Total Weight (lb.)
First Truck	12,700	20,300	19,500	52,500
Second Truck	12,900	21,000	19,700	53,600

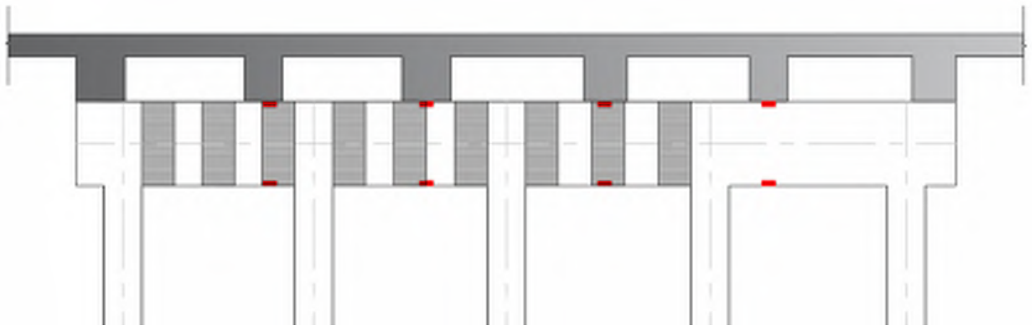


Strain gage locations for bent caps 37

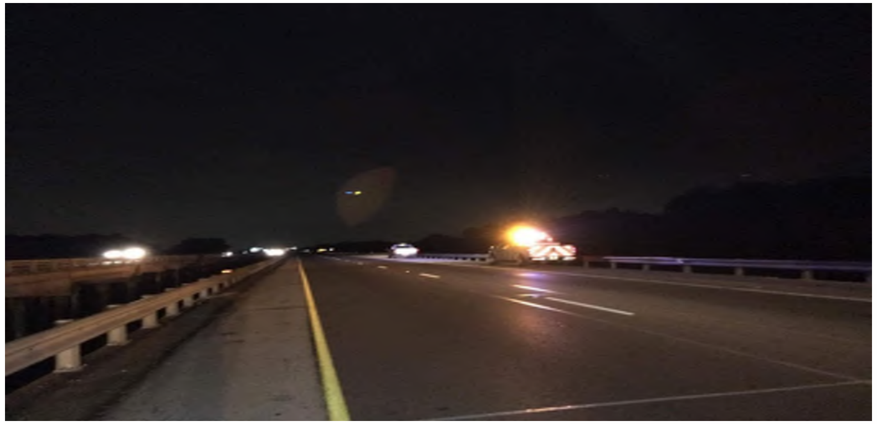


Strain gage locations for bent caps 36

Instrumentation and Load testing



Strain gage locations for bent cap 35



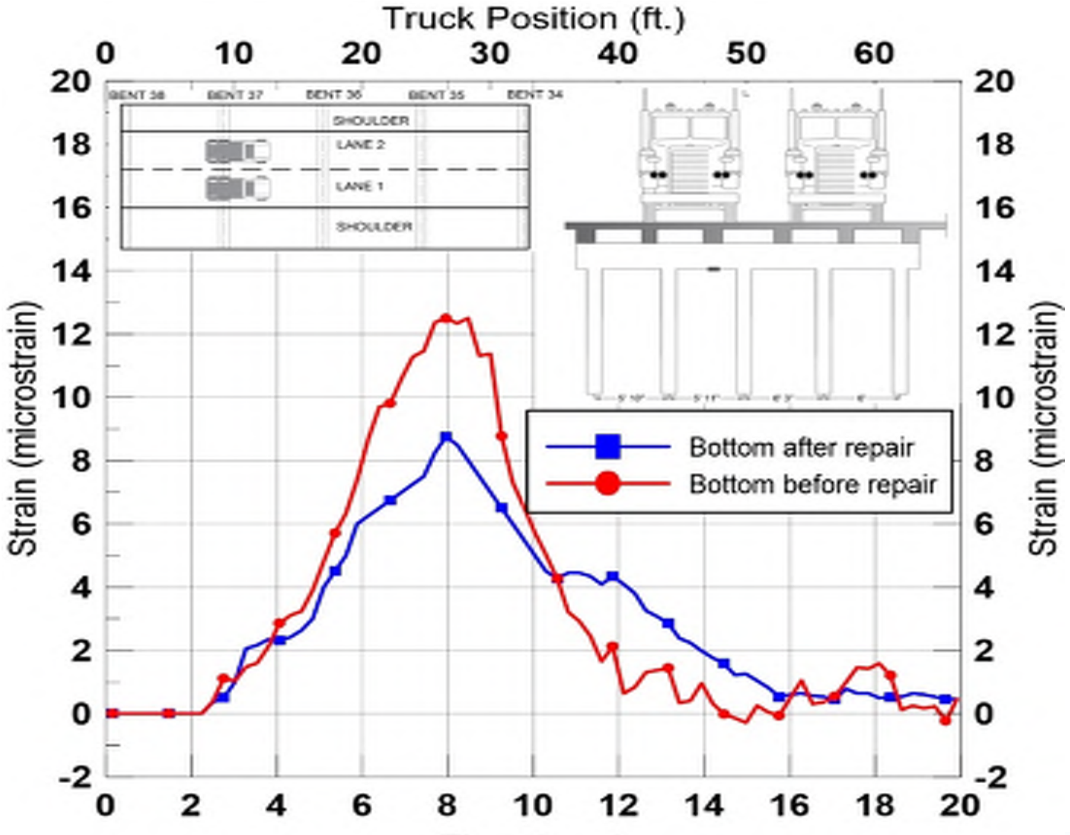
Load Test Results

- The peak strains from all the tests were just around 20 microstrains.
- Relatively low weight of the test trucks, stiff bridge, and short bent cap spans.
- The bridge behaved linear-elastically since the strain readings returned to zero once the trucks were removed.

Load Tests Results

Strain comparisons, before and after repair

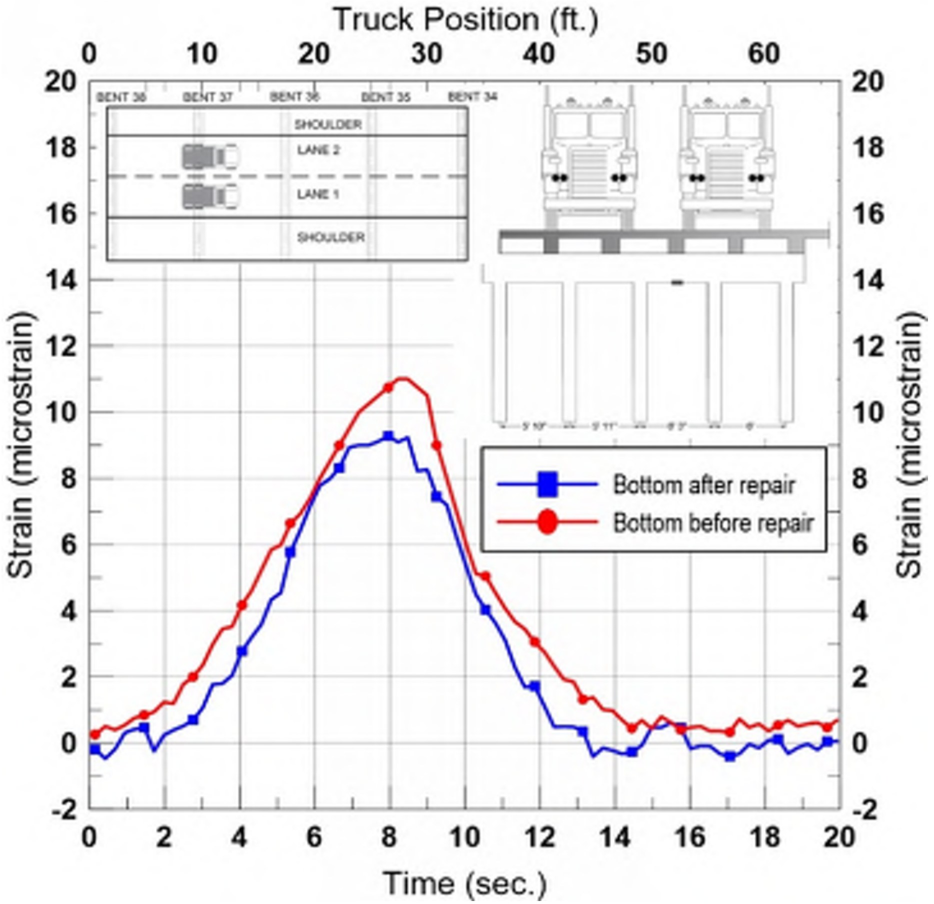
- Crawl speed test with two lanes loaded.
- Reduction in strain after repair for spans two and three in bent cap 37 of 28% and 20%, respectively.



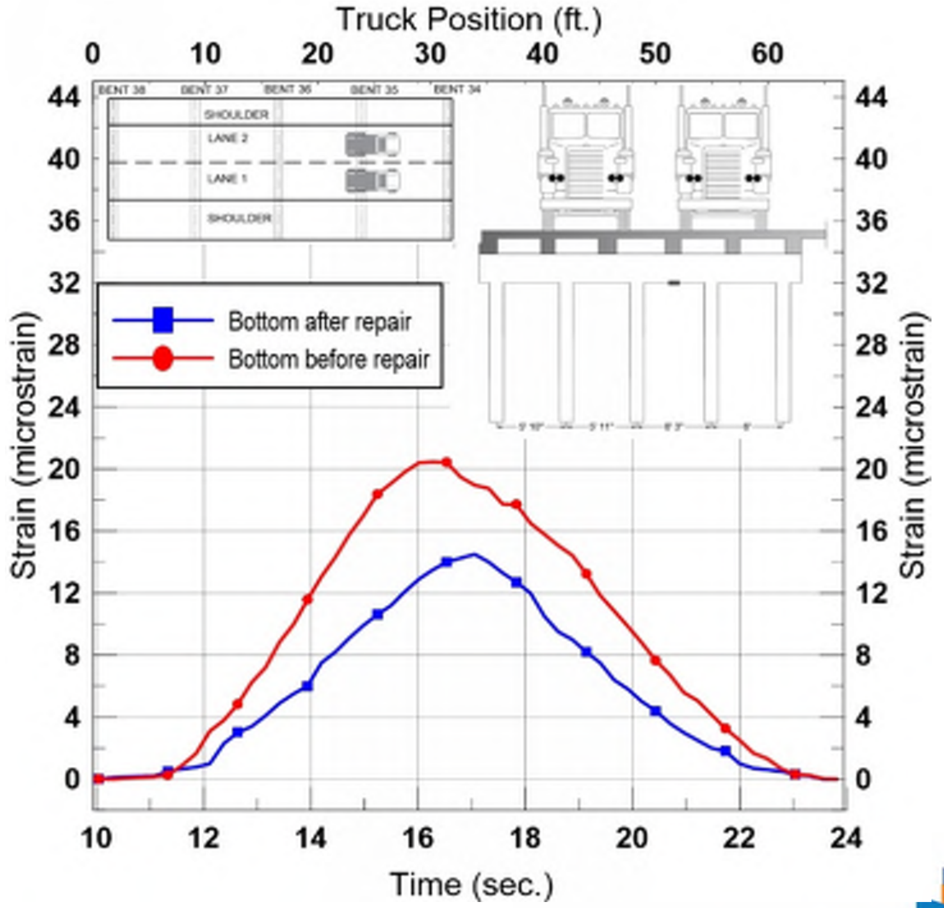
Strain comparison of span two of bent cap 37

Load Tests Results

❑Strain comparison, before and after repair



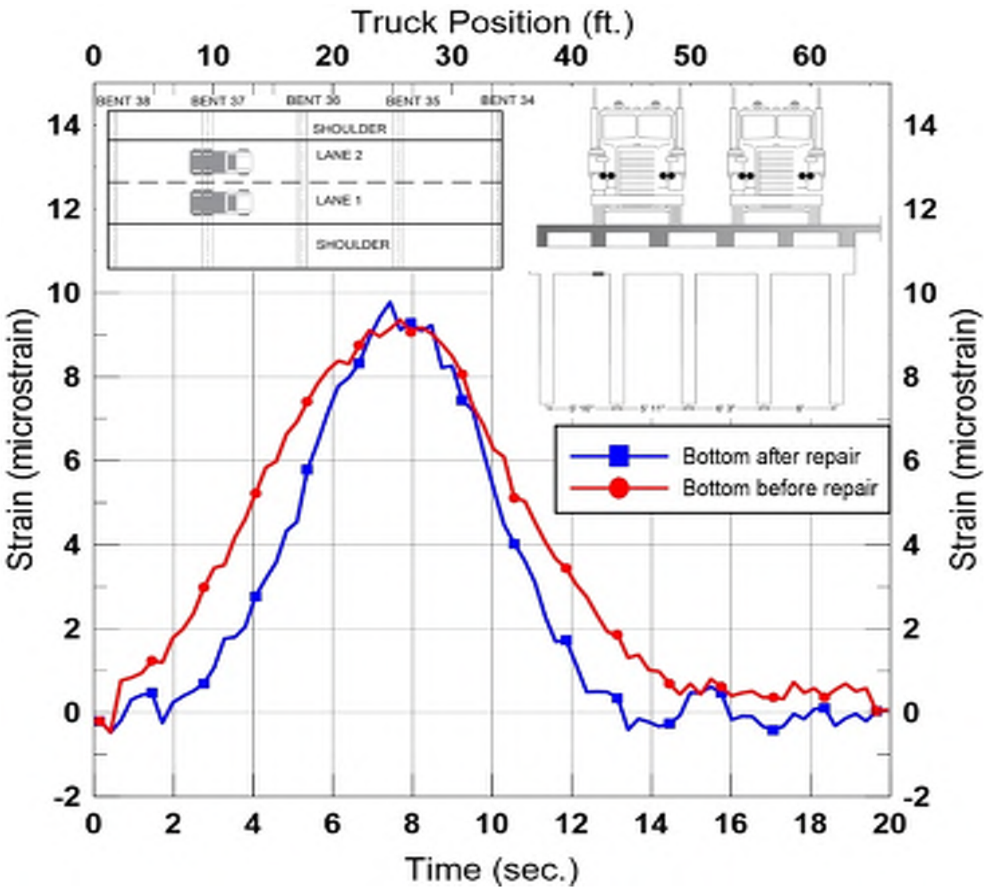
Strain comparison of span three of bent cap 37



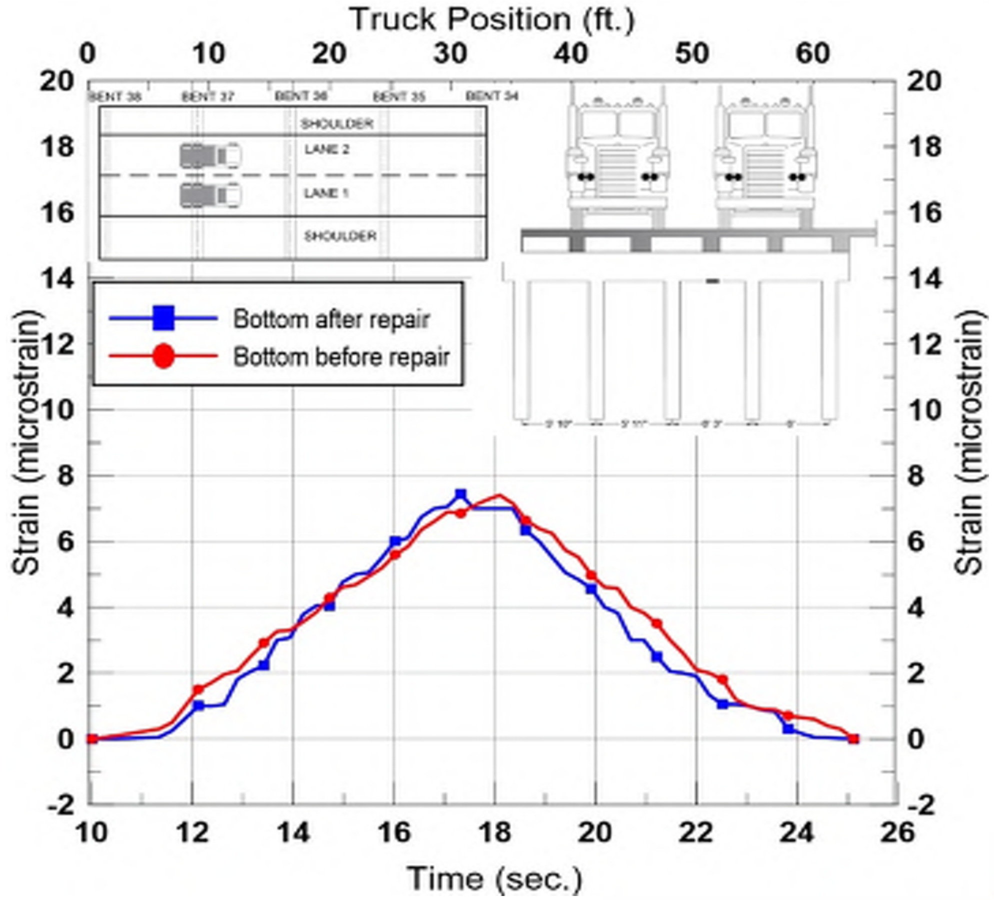
Strain comparison of span three of bent cap 35

Load Tests Results

❑Strain comparison, before and after repair



Strain comparison of span one of bent cap 37

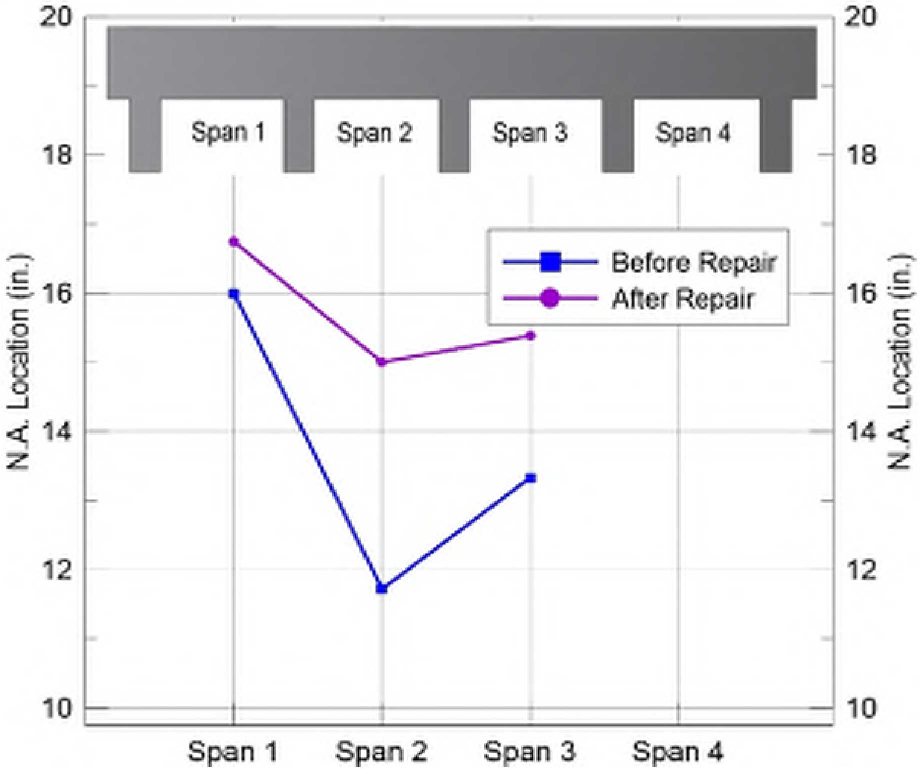


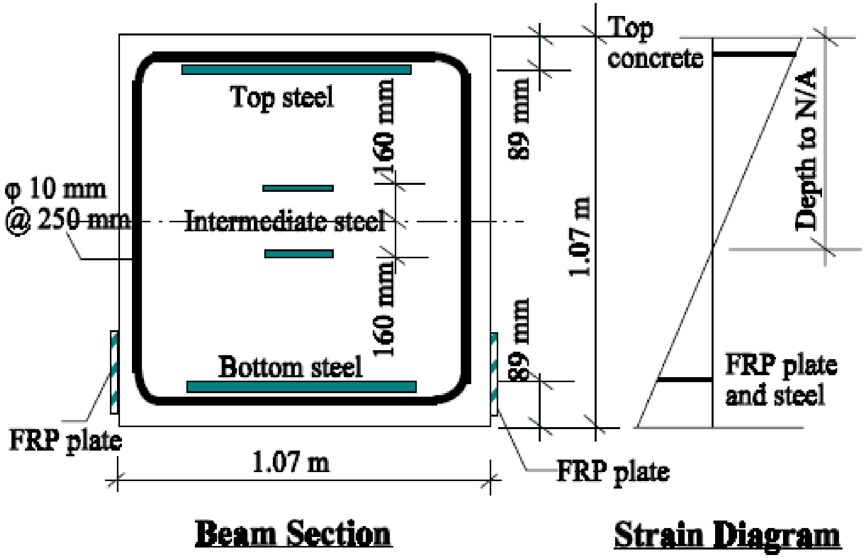
Strain comparison of span one of bent cap 35

Load Tests Results

❑Neutral Axis Location

- The neutral axis moved slightly downwards after the FRP system was installed since the FRP reduced the strain at the bottom face.





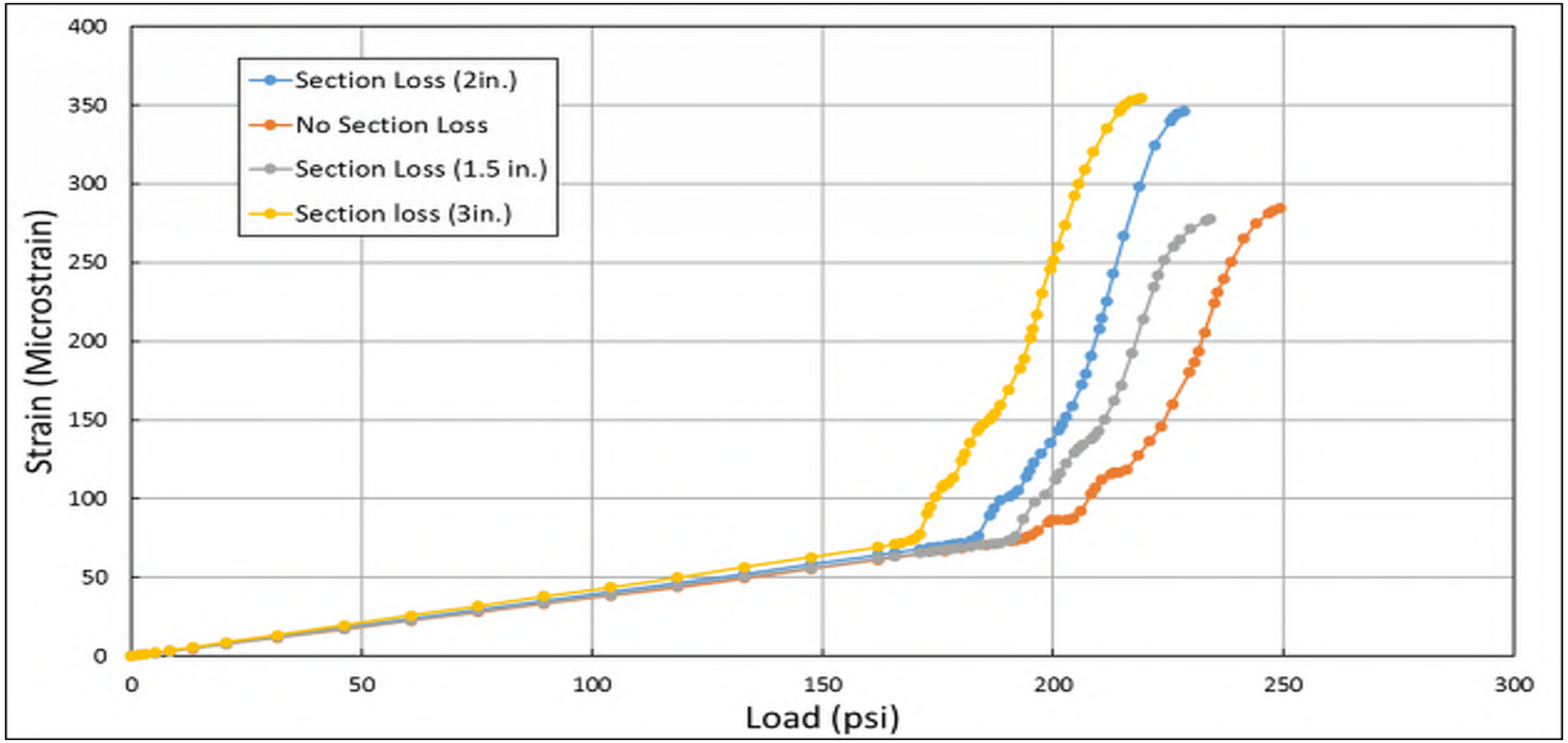
$$c = d - \frac{\Sigma b * d}{\Sigma t + \Sigma b}$$

Finite Element Model Results

UNIVERSITY OF TEXAS ARLINGTON

Deterioration Effect

- The tensile capacity decreased with the section loss increased.



Model #	Section loss depth
1	No section loss
2	1.5 in.
3	2 in.
4	3 in.

Model Results

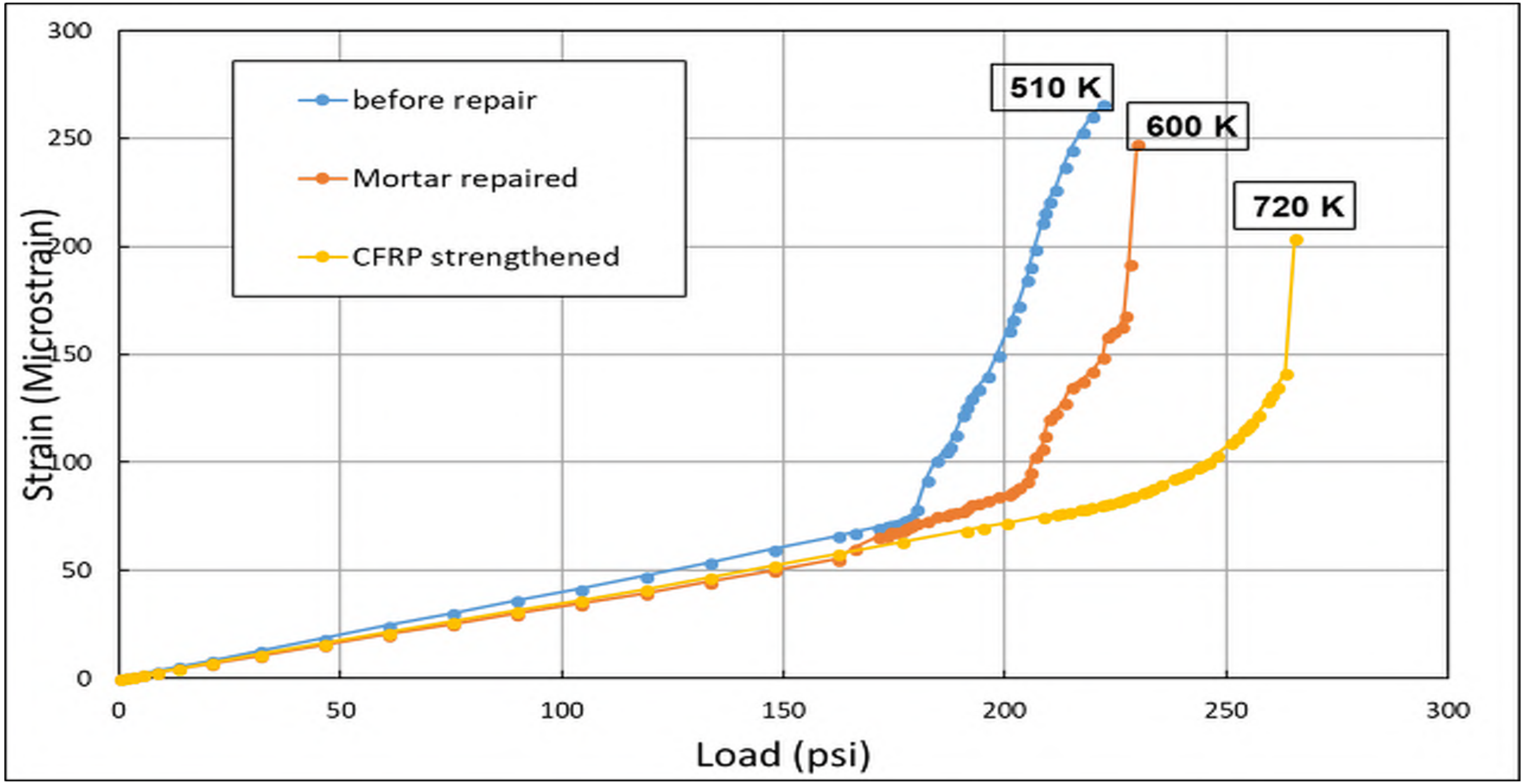
❑ Bent Cap Capacity before and after Repair.

- The applied moment from the truck was around 20 k-ft. which is much less than the cracking moment and the moment capacity.
- The FRP design calculation was found to increase the moment capacity to 381 k-ft. (18%)

Cracking Moment		
	Theoretical (k-ft)	FE Model (k-ft)
Before repair	161	147
After repair	196	238

Model Results (Cont.)

❑ Bent Cap Capacity before and after Repair



Conclusions

- Tensile strain was reduced in two spans by 20 to 28% after CFRP strengthening.
- Application of the CFRP to bent cap rehabilitation was successfully performed with a simple and straightforward process.
- The neutral axis location shifted downwards after the CFRP strengthening.
- No traffic control was needed, except for one hour during load testing.

Conclusions

- The model strain results show a good agreement between the live load data and the finite element model.
- The bent cap section loss resulting from concrete deterioration had a reverse effect on the live load carrying capacity of the bent cap.
- The flexural load-carrying capacity of the damaged bridge was fully recovered and enhanced by applying CFRP sheets on the tensile side of the bent caps.
- Serviceability, especially crack control, was also improved after the CFRP strengthening.

Thank you!

FRP Retrofitting and Non-Destructive Evaluation for Corrosion-Deteriorated Bridges in West Virginia

Wael Zatar, PhD, Marshall University
Hai Nguyen, PhD, Marshall University
Hien Nghiem, PhD, Marshall University

Outline

- Part I: Bridge conditions in West Virginia and Case Studies of WV FRP-Rehabilitated Bridges.
- Part II: Non-destructive testing of reinforced-concrete slabs.

Part I: Introduction

Use of FRP Composites in West Virginia

- According to 2017 National Bridge Inventory (NBI) database (FHWA 2017), West Virginia has 7,228 highway bridges and 19% of these bridges (1,372 bridges) were rated as structurally deficient (SD) and 1,394 bridges (19.3%) were rated as functional obsolete (FO).
- West Virginia has been recognized as a pioneer in the use of FRP composites. FRP composites have been used in the construction of approximately 220 bridges nationwide and 35 of those bridges are in WV.
- There are few FRP-retrofitted bridge projects in WV between 1998 and 2014. Major candidate structures/elements suitable for FRP retrofit include beams/girders, slabs, bents, columns/piles/pier caps, and abutments/footings.

Use of FRP Composites in West Virginia (Cont'd)

- The FRP wraps externally bonded to the concrete surface to compensate for strength lost due to corrosion, deterioration, or fire/impact damage.
- The use of FRP wraps allows the rehabilitation of the existing concrete, resulting in an economic repair as substructure replacement generally requires replacing the entire bridge. These repairs have saved the WVDOT thousands of dollars compared to conventional repairs.

Bridge Conditions in West Virginia

Owner	Bridge Counts				Bridge Area (Square Meters)			
	All	Good	Fair	Poor	All	Good	Fair	Poor
State	6,993	1,814	3,700	1,479	3,569,116	694,518	2,292,099	582,499
County	1	1	0	0	320	320	0	0
Town	0	0	0	0	0	0	0	0
City	101	17	53	31	48,340	4,884	29,117	14,339
State Park	23	8	13	2	2,777	726	1,831	219
Local Park	0	0	0	0	0	0	0	0
Other State Agency	2	1	1	0	662	354	308	0
Other Local Agency	9	1	4	4	2,092	126	1,453	514
Private	4	1	3	0	4,223	103	4,120	0
Railroad	5	0	1	4	9,401	0	115	9,285
State Toll	99	4	93	2	171,012	505	165,291	5,216
Local Toll	0	0	0	0	0	0	0	0
Federally Owned	54	14	31	9	11,487	1,707	8,514	1,266

East Street Viaduct in Parkersburg, West Virginia

- The RC bridge was built in 1907 with two traffic lanes under and 6,748 average daily traffic (as of 2015).
- Single span with a span length of 23.3 ft. and a length of 64.7 ft
- The substructure is composed of unreinforced concrete full-height abutments, RC wing walls, and bents.
- The superstructure consists of 3 ft. RC top slab, which carries 2.5 ft. of railroad slag fill and ten sets of railroad tracks.
- The bridge was rehabilitated in 2001 with GFRP wrapping of the abutments, wing walls, concrete bases of the bents, and top slab. In July 2012, WV State Forces, touched up the FRP on the headwall above the southbound lane with fiberglass repair kit, applied paint to GFRP areas showing wear, and repaired the weep drains.

East Street Viaduct (Cont'd)

Elevation and end views

GFRP Wrapping on a headwall and a wing wall

Flag Run Bridge in West Virginia

- The RC bridge was built in 1940 with two lanes of traffic and 650 average daily traffic (as of 2014).
- It has a single span with a total length of 43.2 ft. (40 ft span).
- The superstructure consists of four RC T-beams (33 in. high and 16.5 in. wide) topped with cast-in-place RC slab and supported by two full-height concrete abutments.
- Entire bottom face and side faces at both ends of T-beams were wrapped with CFRP composites in 2002. Abutments were also wrapped with CFRP and the backwalls were patched.

Flag Run Bridge (Cont'd)

Elevation and end views

CFRP wraps in abutments and underside of a T-beam

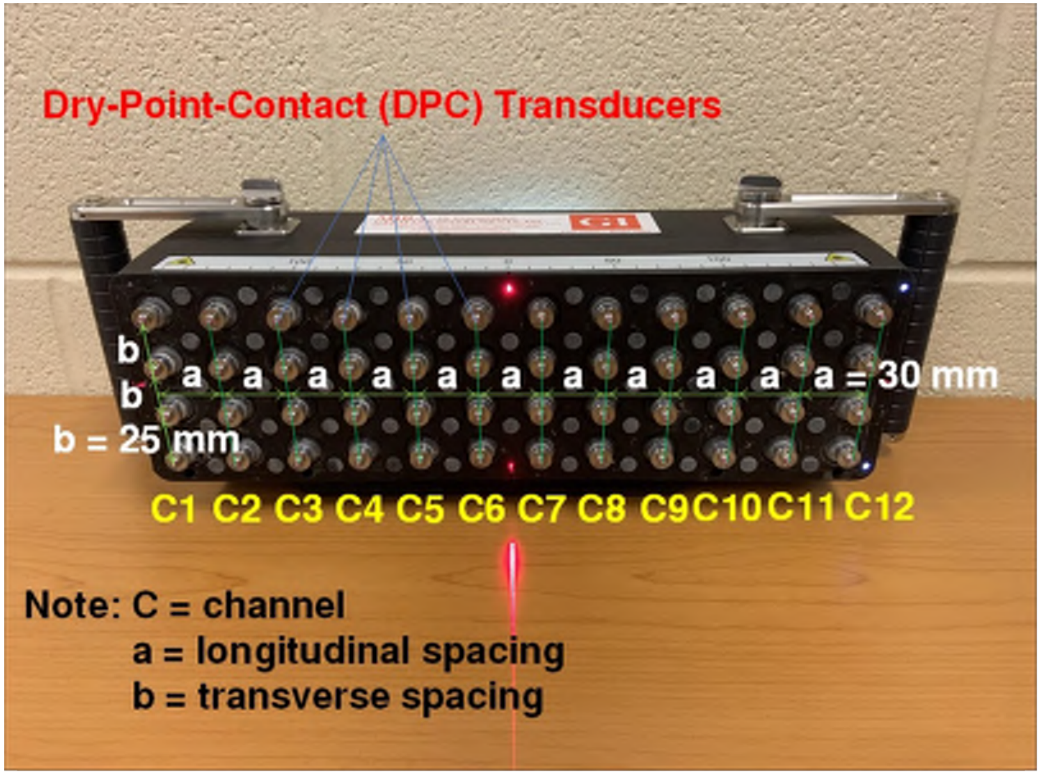
Outline

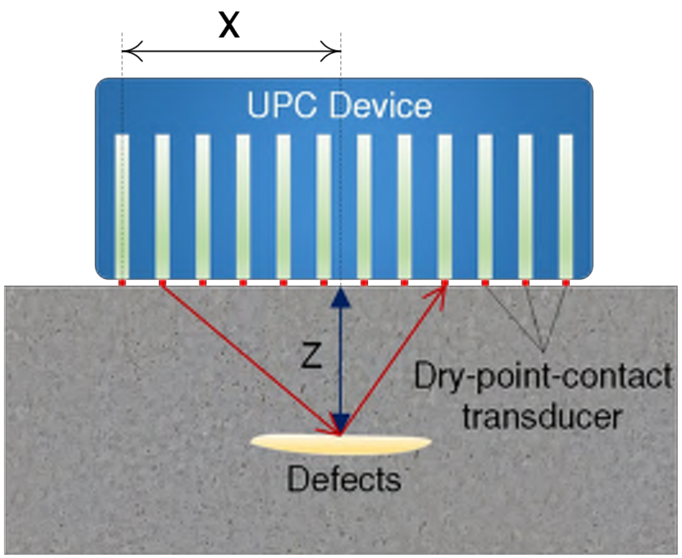
- Part I: Bridge conditions in West Virginia and Case Studies of WV FRP-Rehabilitated Bridges.
- Part II: Non-destructive testing of reinforced-concrete slabs.

Part II: Introduction

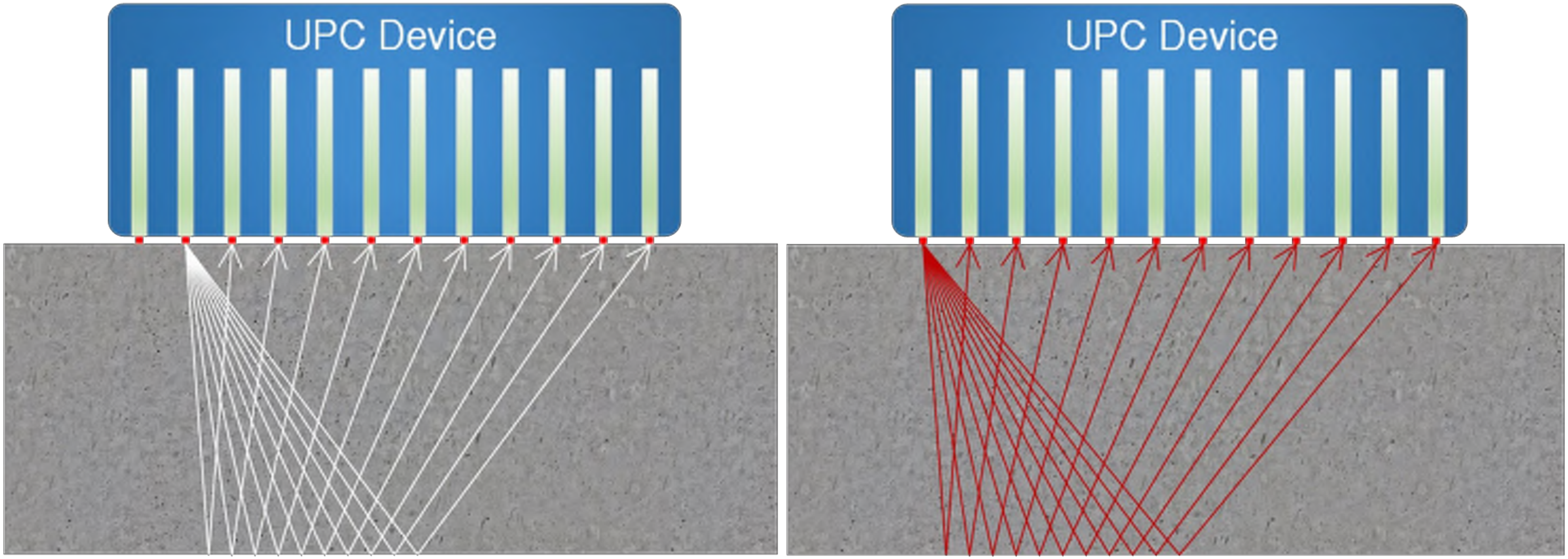
- Design drawings of many aging bridges may not be available which makes prediction of the remaining structural capacities of the bridge components more challenging, or even impossible.
- Fortunately, advanced non-destructive testing (NDT) techniques can provide great solutions to address the deteriorated bridges.
- In this part, the ultrasonic pitch & catch (UPC) technique for imaging concrete structures are discussed.

Basic Principles of UPC Technique





Basic Principles of UPC Technique (Cont'd)

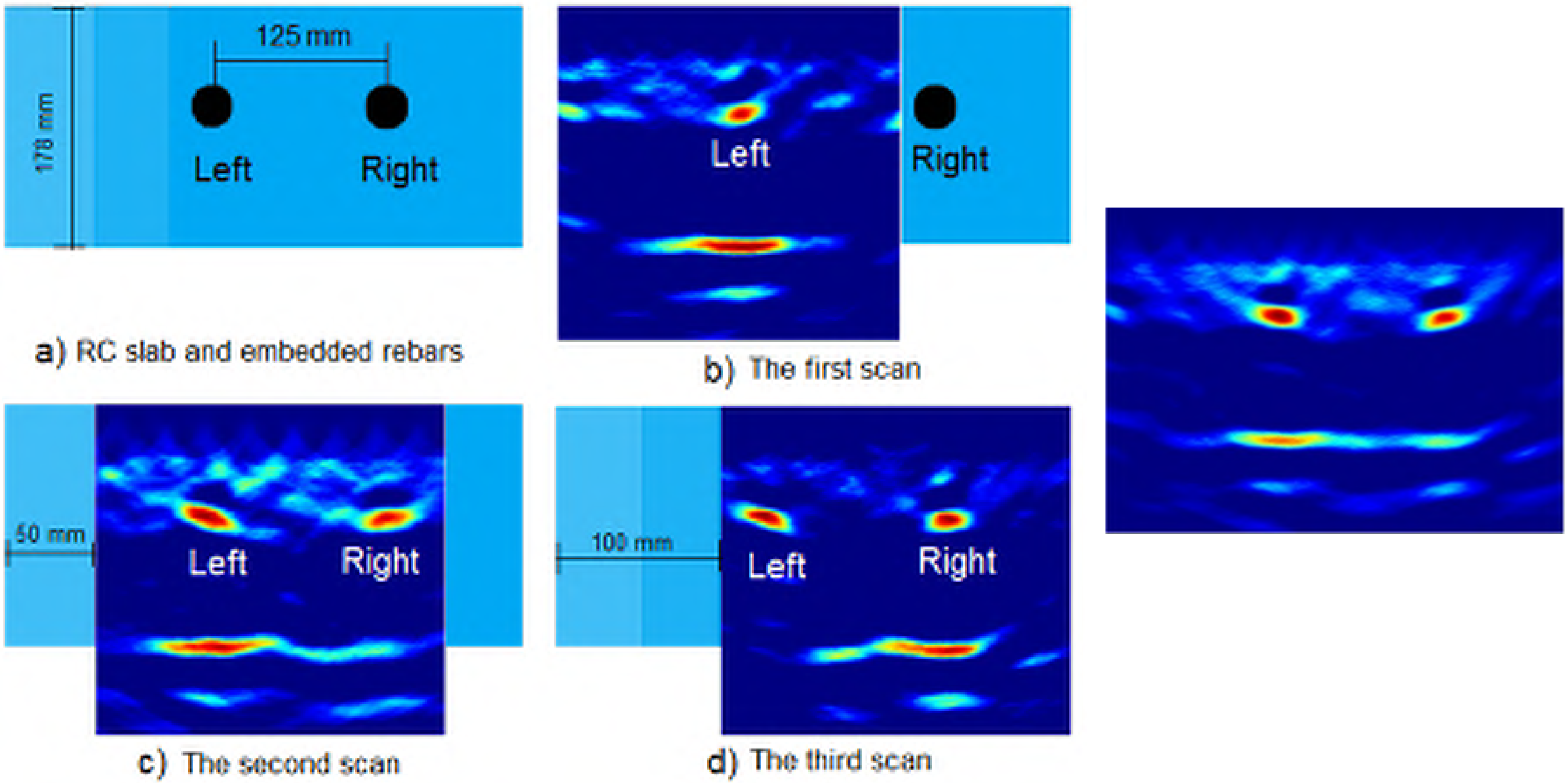


$$d \approx C\frac{\Delta t}{2}$$

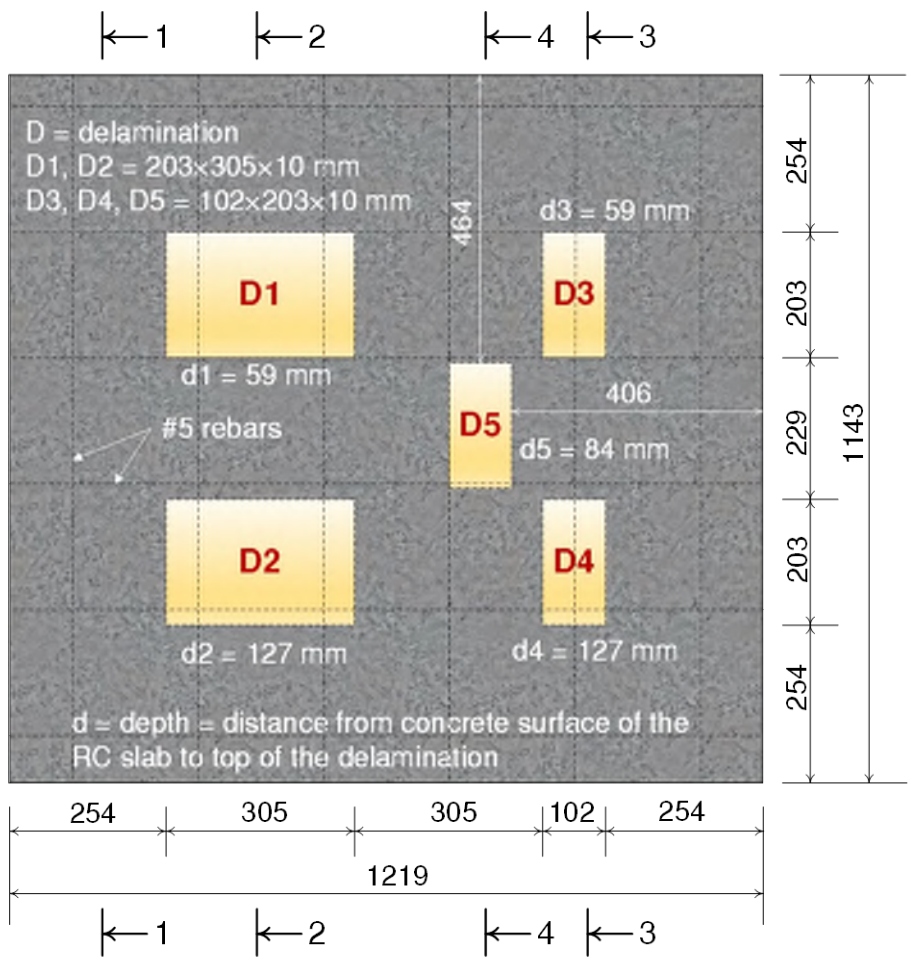
C = Wave Speed

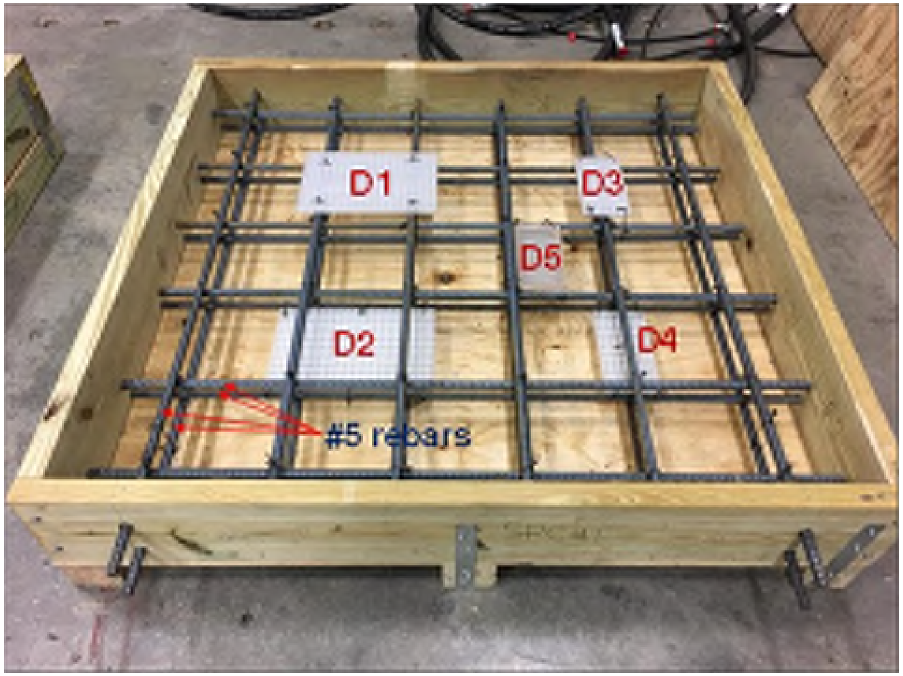
$$N = 1 + 2 + 3 + \cdots (n-1) = \frac{(n-1)n}{2} = 66$$

Synthetic Aperture Focusing Technique (SAFT)



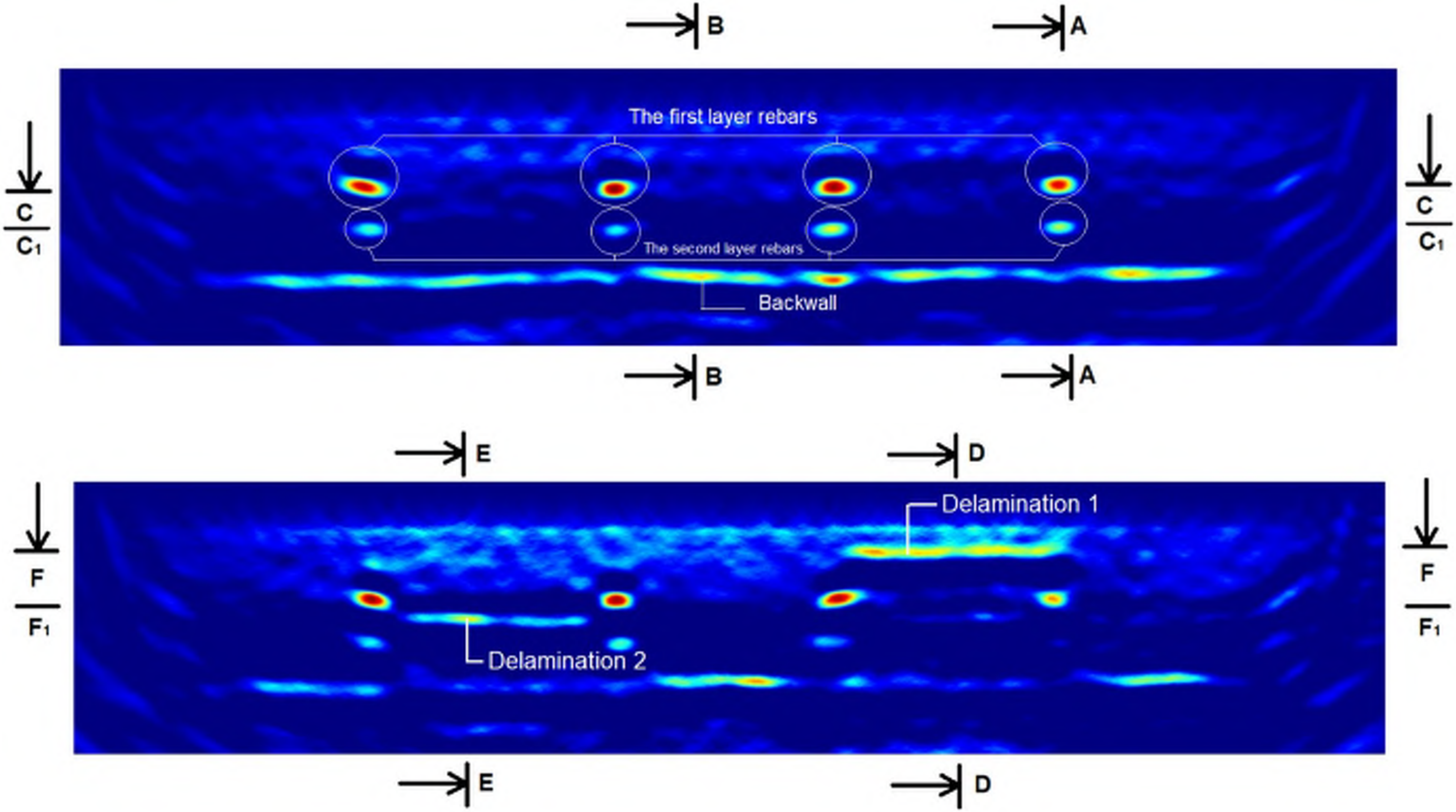
Specimen Preparation and Test Parameters



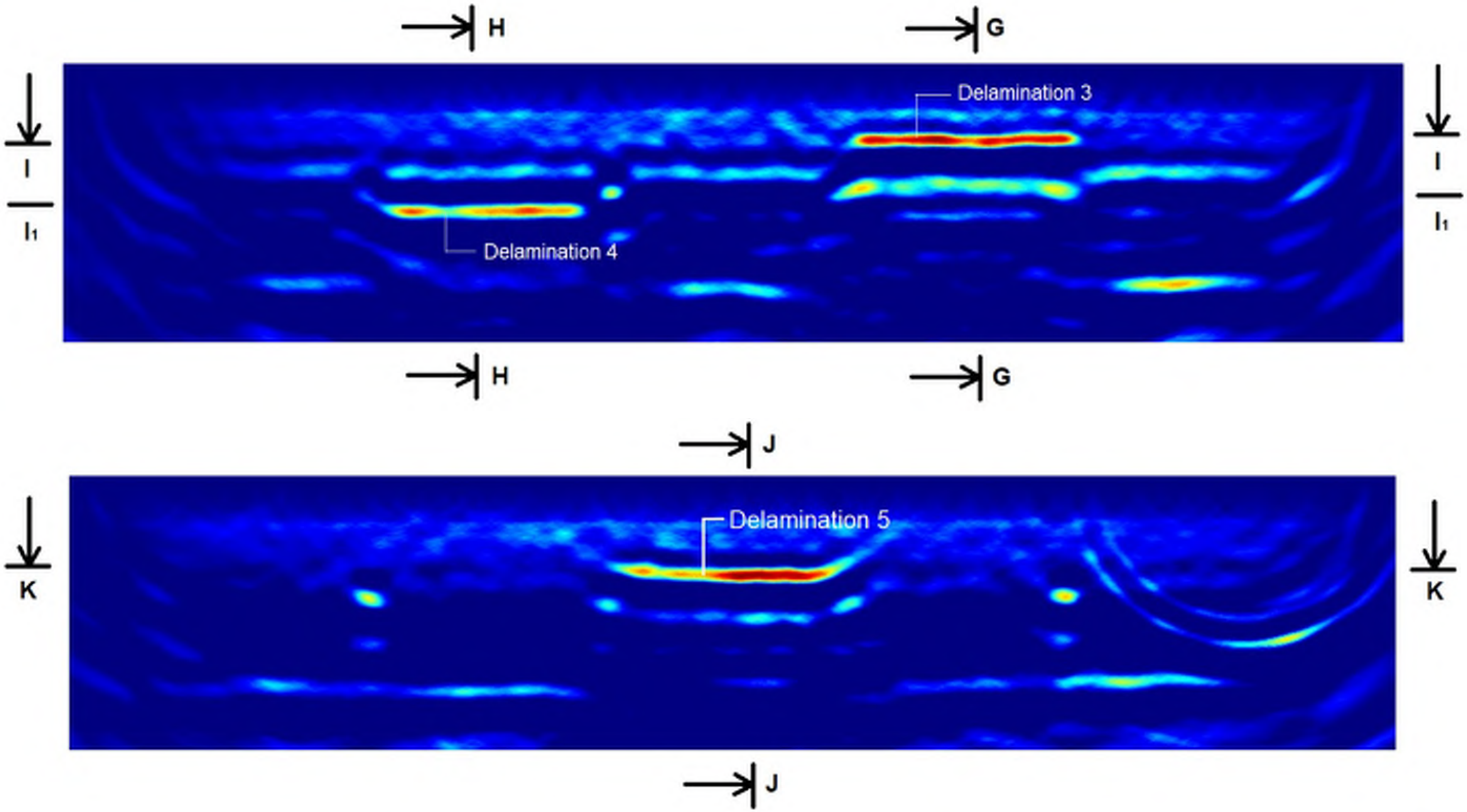


Pre-planned delaminations with various sizes and depths

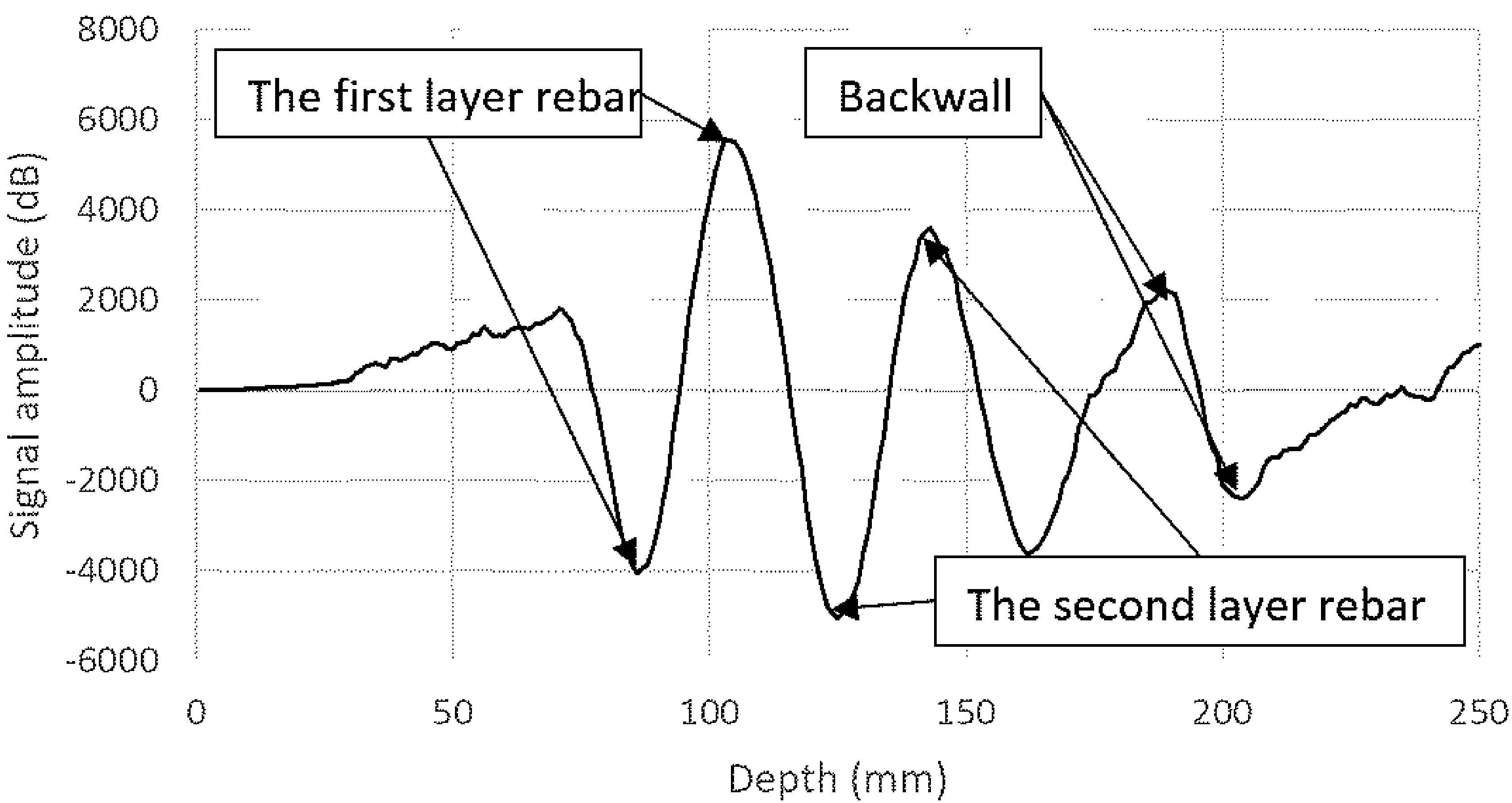
Test Results



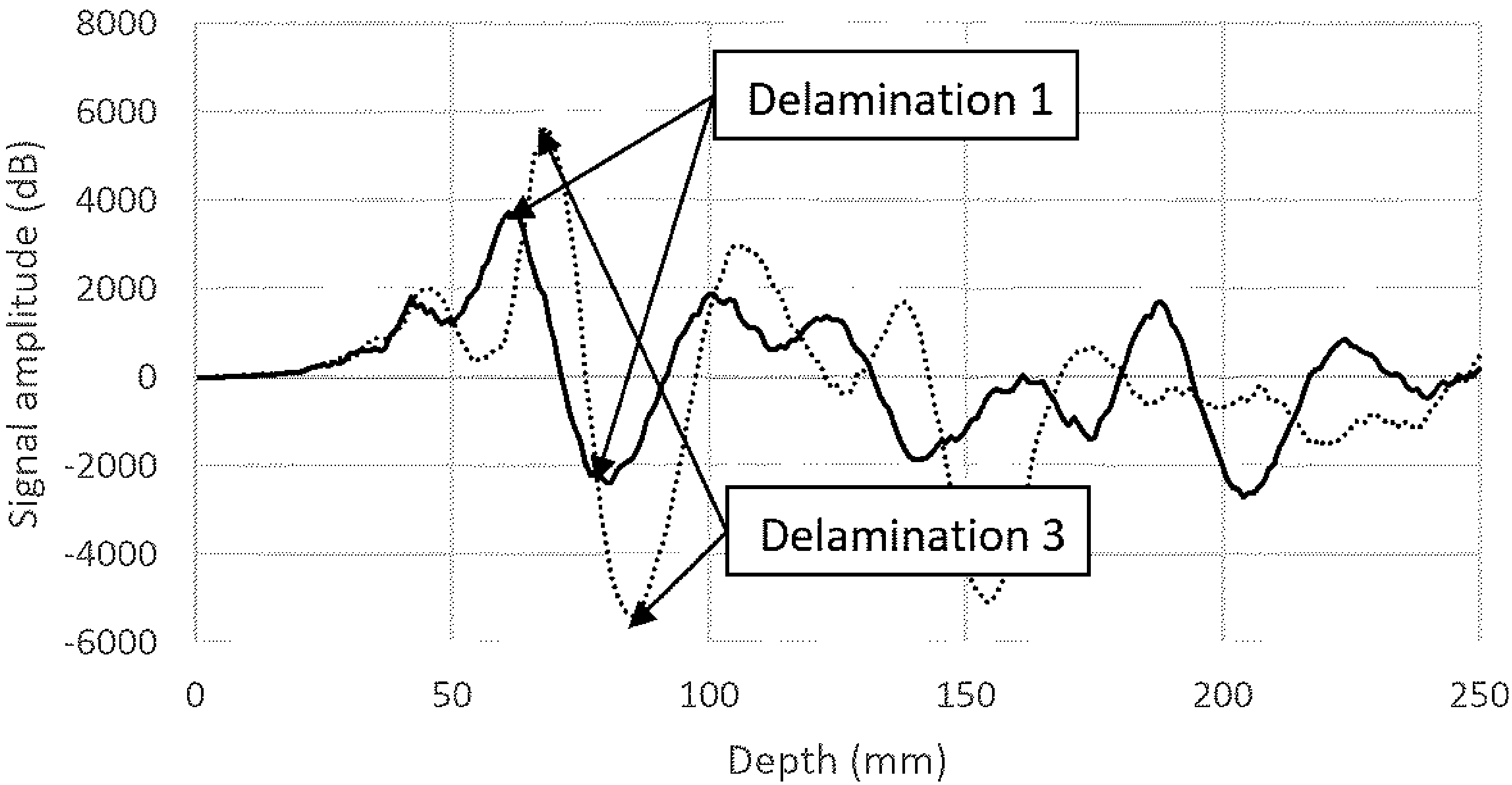
Test Results (Cont'd)



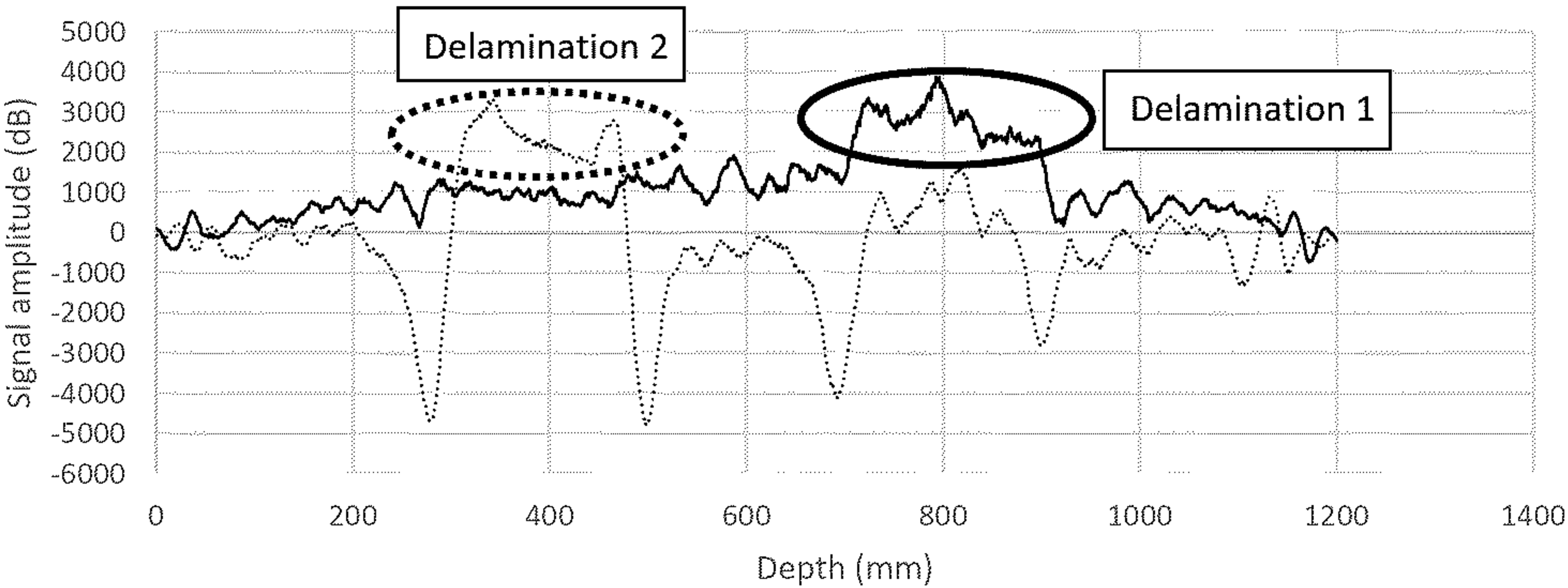
Test Results (Cont'd)



Test Results (Cont'd)



Test Results (Cont'd)



Results (Cont'd)

Delamination	Predicted breadth in. [mm]	Measured breadth in. [mm]	Predicted depth in. [mm]	Measured depth in. [mm]
D1	7.71 [196]	8.00 [203]	2.44 [62]	2.32 [59]
D2	7.05 [179]	8.00 [203]	5.08 [129]	5.00 [127]
D3	7.87 [200]	8.00 [203]	2.36 [60]	2.32 [59]
D4	7.32 [186]	8.00 [203]	5.23 [133]	5.00 [127]
D5	7.48 [190]	8.00 [203]	3.31 [84]	3.62 [92]

Conclusions

- 2D reconstructed images of the rebars and delaminations can be interpreted based on specific patterns of color spectrum.
- The ultrasonic pitch and catch (UPC) is proved to be an excellent NDT technique for an accurate evaluation of concrete structures.
- Applications of other NDT techniques such as GPR and IRT for examining internal defects (e.g., voids, debondings, delaminations) of FRP-wrapped structures will be investigated in future works.

Thank you for your attention!

Bridge Conditions in West Virginia

Main Structure Type	Code	SD (a)	FO (b)	Bridge Total (c)	a/c (%)	b/c (%)
Slab	01	168	144	517	32.5	27.9
Stringer/Multi-beam or Girder	02	592	516	3085	19.2	16.7
Girder and Floorbeam System	03	107	41	229	46.7	17.9
Tee Beam	04	49	25	104	47.1	24.0
Box Beam or Girders - Multiple	05	92	401	1905	4.8	21.0
Box Beam or Girders - Single or Spread	06	2	8	55	3.6	14.5
Frame (except frame culverts)	07	5	14	52	9.6	26.9
Orthotropic	08	0	2	2	0	100
Truss – Deck	09	0	4	11	0	36.4
Truss – Thru	10	78	35	180	43.3	19.4
Arch – Deck	11	159	134	399	39.8	33.6
Arch – Thru	12	1	2	8	12.5	25.0
Suspension	13	2	1	3	66.7	33.3
Stayed Girder	14	0	0	3	0	0
Movable – Lift	15	NA	NA	NA	NA	NA
Movable – Bascule	16	NA	NA	NA	NA	NA
Movable – Swing	17	NA	NA	NA	NA	NA
Tunnel	18	NA	NA	NA	NA	NA
Culvert (includes frame culverts)	19	46	36	539	8.5	6.7
Mixed types	20	1	0	1	100	0
Segmental Box Girder	21	1	1	3	33.3	33.3
Channel Beam	22	63	25	115	54.8	21.7
Other	00	6	5	17	35.3	29.4
Total		1,372	1,394	7,228	19.0	19.3

Major Non-Destructive Testing (NDT) Techniques

Overview of NDT Methods

Acoustic (Stress Waves)

- Pulse-Echo
- Impact-Echo
- Ultrasonic
- Acoustic Impact Testing (a.k.a. Coin Tap Test)
- Acoustic Emission (AE)
- Spectral Analysis of Surface Waves (SASW)
- Parallel Seismic (PS)
- Impulse Response (IR)

Electromagnetic

- Ground Penetrating Radar (GPR)
- Impulse Radar
- Infrared Thermography (IR)
- Conductivity Measurements
- Covermeters (Reinforcing Rebar Locator)
- Radiography (X-Rays, Gamma-Rays, Neutron Radiation, Beta Rays)
- Eddy-Current Testing

Electrical/Magnetic

- Electrical Resistivity (ER) Measurements
- Half-Cell Potential (HCP) Measurements
- Electrical Impedance Tomography (EIT)
- Magnetic Induction
- Magnetic-Flux Leakage

Others

- Visual Testing
- Optical Methods (Shearography, Holography)
- Strain Measurement Techniques (Optical Fibers)
- Penetrant Methods
- Chain Dragging
- Hammer Sounding
- Vibration and Dynamic Testing
- Rapid Load Test
- Coring
- Modal Analysis

Bridge Substructure Repairs with Basalt and Glass FRP Internal Reinforcement

Presented by Mohit Soni, PE, PMP, Peng

Stantec Consulting Services Inc.

1. Introduction
2. Purpose and Need
3. Procedure
4. Pilot Projects
   - US 17 over Trout River Details
   - SR 312 over Matanzas River
5. Testing
6. Lessons Learned
7. Conclusion

Introduction

Florida's Vast Infrastructure

Second longest coastline in the United States (behind Alaska)

122,000 centerline miles of roadway

14,000 bridges (state and non-state)

176M sq.ft. bridge area

Purpose and Need

The Consequences

- Earlier studies, and others, reveal:
  - GFRP exposed to marine environments resulted in degradation of mechanical properties
  - FRP bars embedded in moist concrete had adverse effects on long-term durability

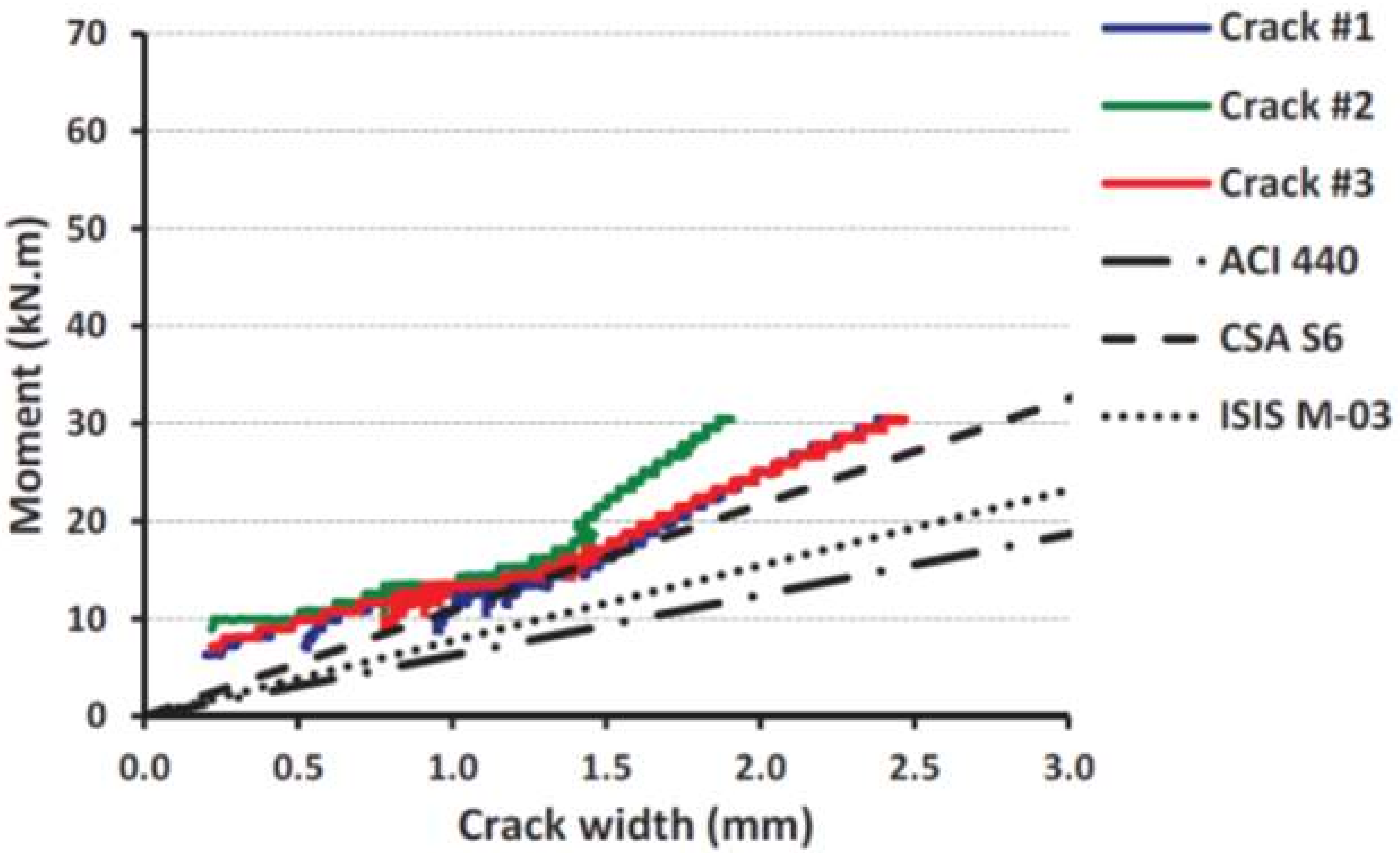
- Therefore use of GFRP was restricted within submerged and splash zones.

FDOT Studies

- Degradation Assessment of Internal Continuous Fiber Reinforcement in Concrete Environment - BDK82-977-05, 2014
- Performance Evaluation of Basalt Fiber Reinforced Polymer (BFRP) Reinforcing Bars Embedded in Concrete - BVD30-986-01, 2018-2019
- Performance Evaluation, Material and Specification Development for Basalt Fiber Reinforced Polymer (BFRP) Reinforcing Bars Embedded in Concrete – BE694, 2019-2021

Studies confirm these methods meet requirements

However implementation required to measure long-term performance in different environments and exposure conditions



Two Projects in Focus

US 17 over Trout River

Bridge No. 720011
Duval County
FDOT District 2

Scope includes:

- Removal of existing jackets from jacketed piles and the design of an impressed current cathodic protection (ICCP) system for previously jacketed piles
- Field identified prestressed concrete piles
- Detail ICCP system for concrete footers at Pier 9 and Pier 10 utilizing GFRP

EB SR 312 over Matanzas River

Bridge No. 780089
St. Johns County
FDOT District 2

Scope includes:

- Design of impressed current cathodic protection system utilizing GFRP and BFRP for the columns
- Struts and footers for piers 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, and 31
- Repair delaminations for columns 28-1, 28-2, and 29-2
- Repair undermined seal for piers 24 and 25

FDOT's Conventional Approach on Preservation

- Cathodic protection
- Concrete rehabilitation using conventional carbon-steel

These pilots utilize alternative innovative reinforcement

- Including GFRP and BFRP

US 17 Over Trout River Details:

27 Spans

Length totaling 1,458 feet

AASHTO Type III

Prestressed beams

20-in. Square

Prestressed pile bents and pile footings

69.75 ft.

Overall bridge width and carries two lanes in each direction

Existing Condition

Existing pier footings and piles severely deteriorated due to spalls and delamination

Reinforcements were exposed with a section loss of 25% or more

Majority of damage occurred within splash zone

Procedure

Substructure component needed to be cleaned

Removal of loose concrete

Verifying reinforcement is robust and continuous

Sensitivity analysis was performed

Sensitivity analysis of piles

Evaluated degree of risk associated with removal of concrete and reinforcement from active piles and footers

Results are reported to contractor

Contractor knows the amount of concrete that can safely be removed

Construction Method

For Pier 10, conventional forming of the jacket and placing concrete was used

Construction Method

Concrete was applied using shotcreting techniques for Pier 9.

Concrete quality issues

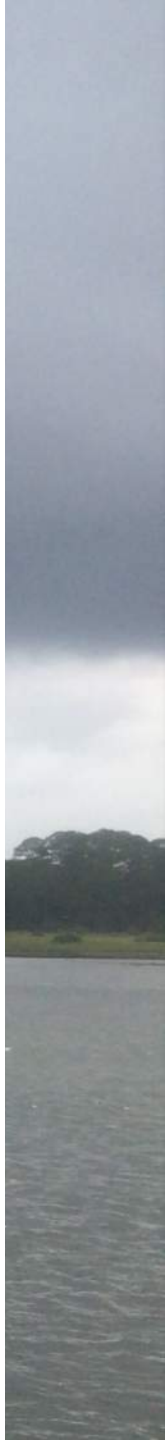
- Provided opportunity to explore removal of concrete from FRP bars

Innovations

- Utilization of GFRP bars in a variety of setting, including conjunction with shotcrete and conventional cast-in-place method
- Utilization of GFRP bars within the splash zone/marine environment will support the outcome of the studies for lifting restrictions

US 17 over Trout River

SR 312 over Matanzas River



SR 312 Over Matanzas River Details:

37 Spans

Length totaling 3,575 feet

AASHTO Type IV

Prestressed beams for approach spans and steel plate girders for 3-span channel unit

20-in. Square

Substructure comprised of 2-column piers supported by waterline footings

47.25 ft.

Overall bridge width and carries two lanes in each direction

Work Activities on SR 312

- Removal of existing multi-column pier jackets and installation of new jackets on multi-column pier
- Pier footing jackets with ICCP installed
- Ribbon anodes installed between piles on pier footing
- GFRP dowels and BFRP mesh were used in select locations

- Pier 15, 19, 20, 21, 22, 23, 26, 29, 30 and 31 were rehabilitated as follows:
  - Columns: No. 4 L-shape GFRP dowel bars were embedded into the columns to attach the 6-in. x 6-in. x 5/32-in. (150mm x 150mm x 4mm) BFRP mesh for crack control to protect the titanium anode mesh.
  - Footing Struts: No. 4 L-shape GFRP dowel bars were embedded into the strut to attach the No. 4 GFRP bars in longitudinal and No. 3 GFRP bars in transverse direction to protect the titanium anode mesh. Dowel spacing was 6-in. and GFRP bars were spaced at 1-ft. in both directions alongside of the strut.
  - Footing: This is among the first FDOT projects to implement ribbon anodes.

Existing Condition

Existing pier footings and piles severely deteriorated due to spalls and delamination

Reinforcements were exposed with a section loss of 25% or more

Majority of damage occurred within splash zone

Construction Method

Unexpected conditions

Construction Method

Previous spall/crack repairs did not work, one of the reasons was missing of ties at the bottom of the columns

Construction Method

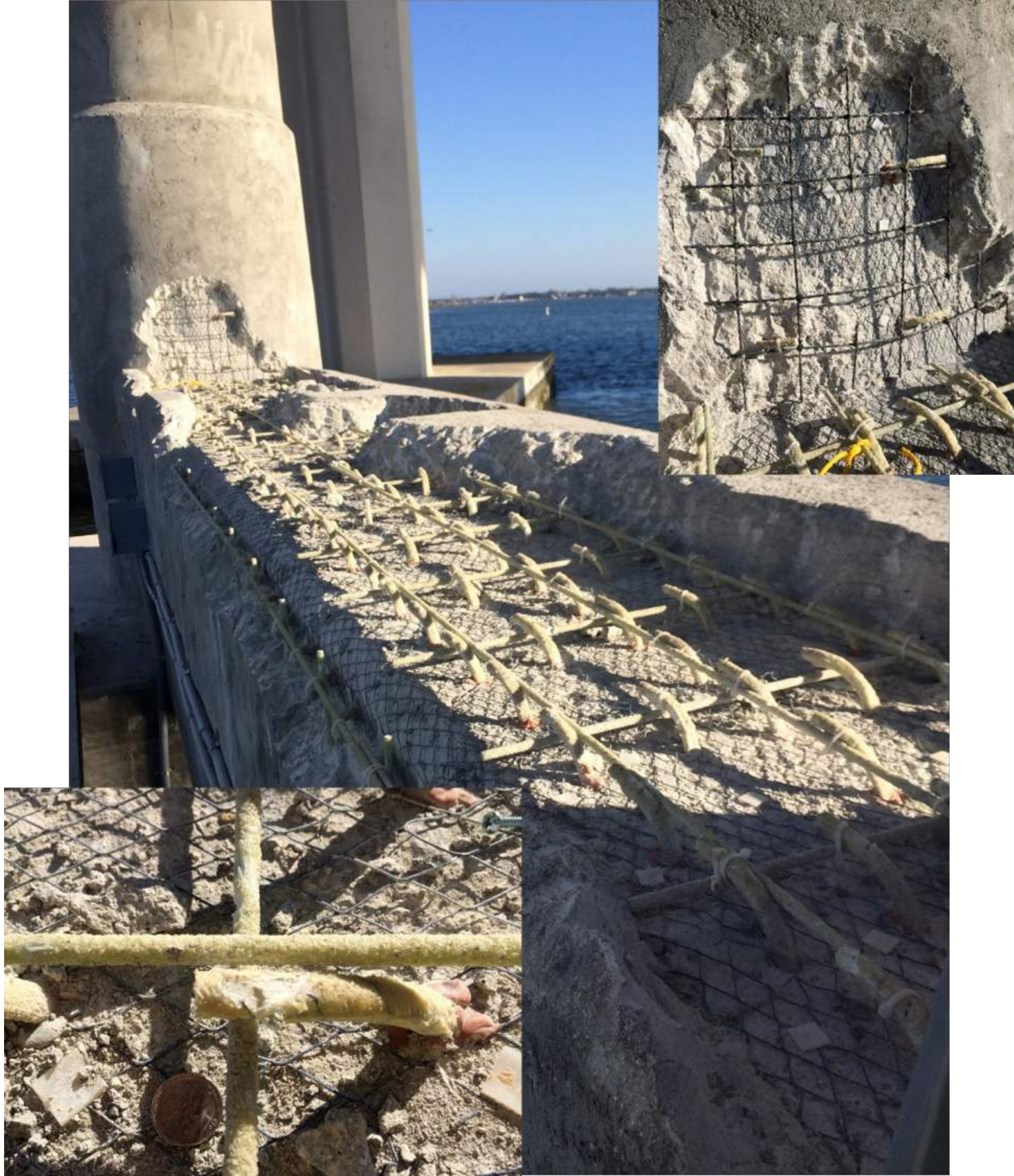
Forming and pouring of columns damaged section after installation of ties

Construction Method

Shotcrete was used in the column and strut to form the jacket

Innovations

- Use of GFRP (ECR-VE) bar in conjunction with shotcrete
- Use of BFRP (Basalt-Epoxy) mesh in conjunction with GFRP (ECR-VE) bar
- Use of ribbon anodes in footings for cathodic protection of remaining carbon-steel reinforcing
- GFRP (ECR-VE) bar use in the marine environment
- Utilization of GFRP bars within the splash zone/marine environment will support the outcome of the studies for lifting restrictions



Construction Method

Finished Jackets

Testing


Shotcrete Adhesion Test Panels
South Side of Pier 9 Strut
Abrasive Blast Surface Prep
Abrasive Blast Prep + Titanium Mesh
5000psi Pressure Wash Surface Prep
All saturated surface dry prior to shotcrete application
WALSH
THINK SAFETY

The surface of GFRP bars were provided with sand coating that promotes bond adhesion of the bar to shotcrete

Surface preparation was found to be adequate for bonding as defined by ACI 548.11R-12. for SR 312 over Matanzas River Testing

Lessons Learned

Challenges overcome for both projects:

- Longer lead times than typically expected for steel rebar was required for the procurement of GFRP due to the production shop availability for bending/fabrication GFRP bars as well as both GFRP and BFRP producers were not available locally.
- For pilot projects take into account the availability of experienced workers on similar technology as the technology was implemented for the first time in the state.
- GFRP/BFRP material storage guidelines and specifications including the temperature were not available in the FDOT specifications.
- Limitations on the field modifications associated with the reinforcing due to the shop bending/fabrication of the bars.
- Location of the site in relation to the concrete plant provided tight time intervals to place the concrete, possibly contributing to the poor placement of the shotcrete.
- Very little to no damage was observed after removal of concrete from BFRP mesh and GFRP bars and this reinforcing was then successfully reused.
- Shotcreting techniques require very strict quality control in mix design, temperatures as well as nozzle man skill and qualification for its success.

Conclusion

Conclusion

US 17 over Trout River Bridge and EB SR 312 over Matanzas River Bridge incorporated numerous innovations as pilot projects. In the end, both projects were successfully constructed and are being monitored long-term by the FDOT State Materials Office. The technologies and innovations implemented in both projects are associated with the usage of FRP is performing well and as a result partially contributed to FDOT lifting the restrictions on the usage of GFRP bars in the marine environment and implemented this innovative technology in several recent projects.

Questions


ME
THANK YOU
THANK YOU
THANK YOU
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THANK YOU
THANK YOU
THANK YOU
THANK YOU
THANK YOU
STAY 6 FEET AWAY

TYLININTERNATIONAL

Shear Strengthening of Beams on the Sunshine Skyway Bridge Trestle Spans with CFRP

aci

October 28, 2020

Sunshine Skyway Bridge History

- Original Sunshine Skyway Bridge 1959
- Twin Structure 1971

Summit Venture Disaster May 9, 1980

Atiq Alvi, PE

Vice President/Technical Director - Bridge Rehabilitation

- Engineer of Record for 3rd CFRP Strengthening Project 2019
- Project Manager for Pilot CFRP Project 2007
- Project Manager for Skyway Trestle Span Beam Study 2006
- Technical Director for Bridge Rehabilitation
- Former FDOT District Seven Structures Maintenance Engineer
- PM/Engineer of Record for 50+ rehab projects, including movable and complex bridges
- Transportation Research Board Bridge Structural FRP Committee since 2003

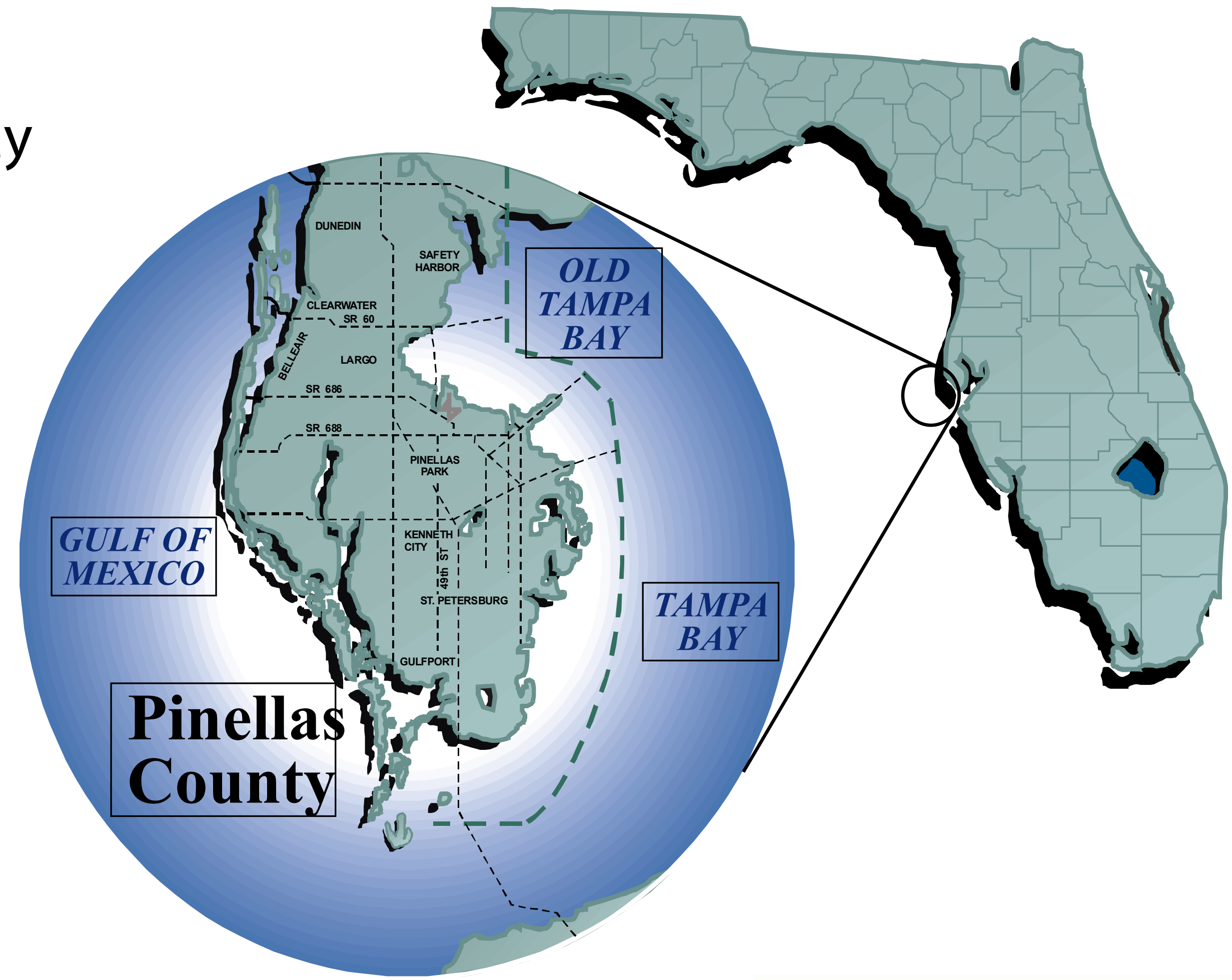
Outline

- Sunshine Skyway Bridge, 1987
- AASHTO Beam Cracking, 1990s
- Investigation/Studies, 2006-2009
- Repair Projects, 2007, 2013, 2020
- Summary

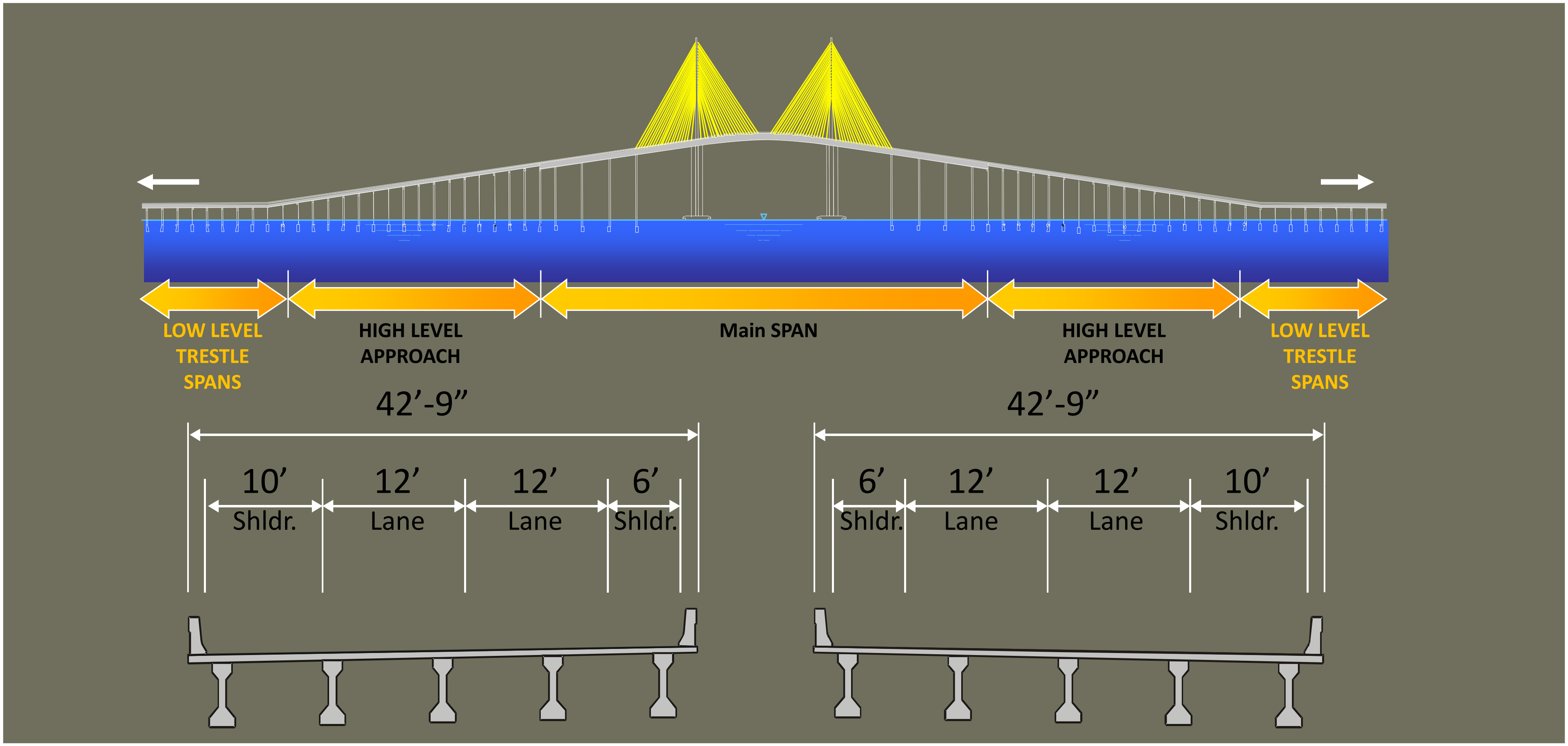
Bob Graham Sunshine Skyway Bridge 1987

Location

- Carries I-275 over Tampa Bay
- 4.14 Miles in Length
- Crosses Three Counties
  - Pinellas
  - Manatee
  - Hillsborough



Bridge Geometry



Trestle Spans Length: 13,000 feet

Typical Diagonal Cracking

- Detected in mid-1990s
- Begins in Web
- Propagates at <u>20º</u> to <u>45º</u>

Typical Diagonal Cracking

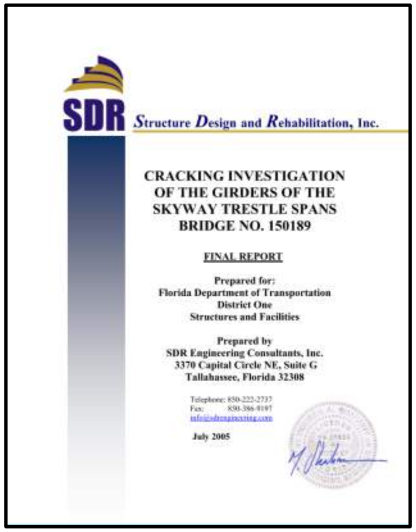
- Shear Cracking in Web Extending to Bottom Flange

Typical Diagonal Cracking

- Web Shear Cracking

Investigations and Studies

- Several Special Inspections
- In-Depth Investigation and Study
- Replicated Beams and Testing


SDR Structure Design and Rehabilitation, Inc.

CRACKING INVESTIGATION OF THE GIRDERS OF THE SKYWAY TRESTLE SPANS BRIDGE NO. 150189

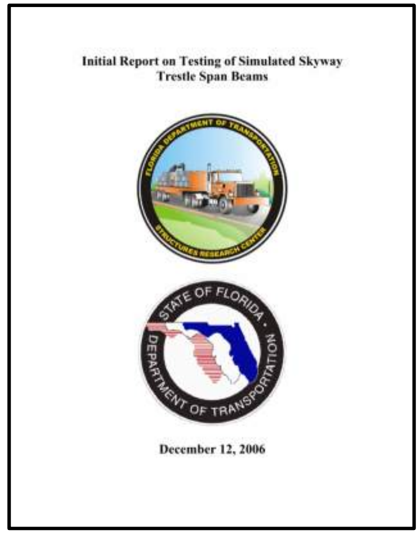
FINAL REPORT

Prepared for:
Florida Department of Transportation
District One
Structures and Facilities

Prepared by
SDR Engineering Consultants, Inc.
3370 Capital Circle NE, Suite G
Tallahassee, Florida 32308

July 2005

FDOT District 1&7 Structures Maintenance Office 2006


Initial Report on Testing of Simulated Skyway Trestle Span Beams

December 12, 2006

FDOT Structures Research Center 2006


University of Florida
Civil and Coastal Engineering

Engineering
University of Florida
Civil and Coastal Engineering

Final Report May 2009

SHEAR PERFORMANCE OF EXISTING PRESTRESSED CONCRETE BRIDGE GIRDERS

H. R. Hamilton III

Gustavo Llanos
Brandon E. Ross

Department of Civil and Coastal Engineering
University of Florida
P.O. Box 116580
Gainesville, Florida 32611

Sponsor:
Florida Department of Transportation (FDOT)
Marcus H. Ansley, P.E. – Project Manager

Contract:
UF Project No. 00056470
FDOT Contract No. BD 545-56

University of Florida 2009

Investigations and Studies

- Reviewed Inspection Reports
- Reviewed Original Design and Construction Plans
- Hands-On Inspection
- Traditional AASHTO Shear Analysis
- Strut and Tie Model
- Non-Linear FEM Analysis
- Performed Load Testing
- Replicated Girders and Load Tested

AASHTO TYPE IV Girder Properties	Value
Compressive Strength of the Girder Concrete	5500 psi
Compressive Strength of the Deck Slab Concrete	4000 psi
Jacking Force	39,600 lb
Initial Prestressing Steel Stress	185.15 ksi
Effective Prestressing Steel Stress after 24% loss	141 ksi
Ultimate Strength of Strands	270 ksi
Maximum Span Length	100.5 ft.
Weight of Barrier	419.0 lb/ft
Unit Weight of Concrete	155 lb/ft3

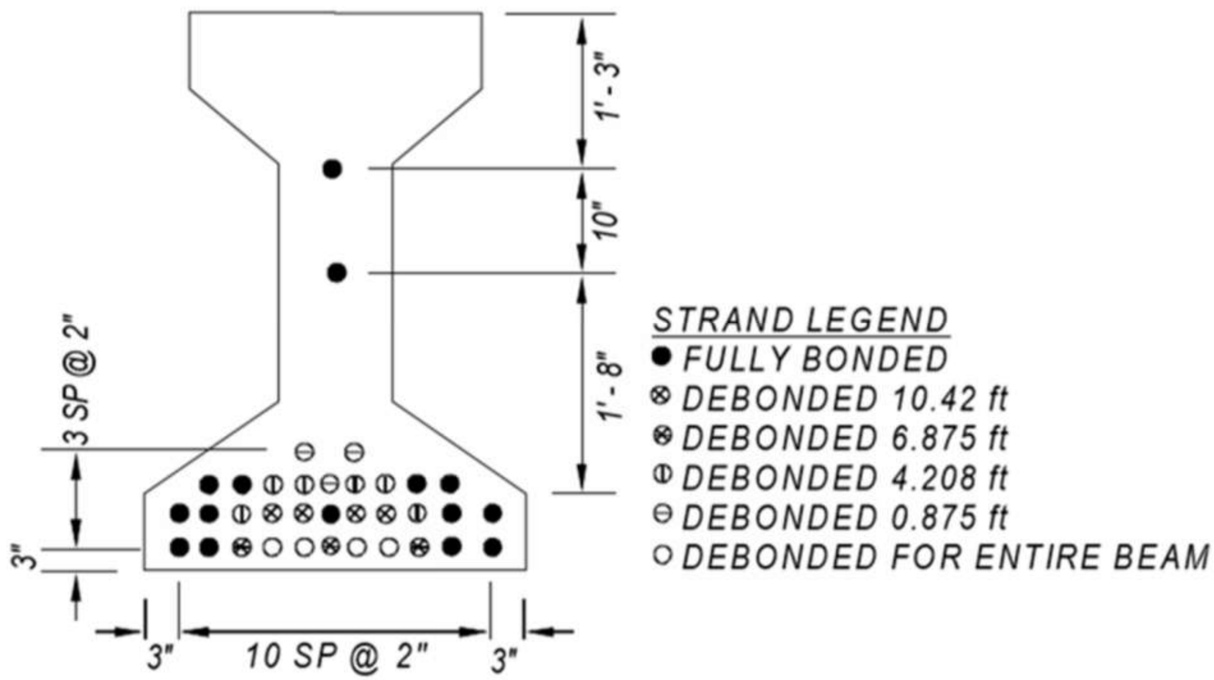
Cracking Summary

Bridge	Girders			Girders w/Cracking				
	Total Girders	Exterior Girders	Interior Girders	Exterior Girders	Exterior %Cracked	Interior Girders	Interior %Cracked	Total %Cracked
Northbound	650	260	390	254	97.7%	4	1.0%	39.7%
Southbound	650	260	390	242	93.1%	5	1.3%	38.0%

* Majority of Diagonal Cracks in Exterior Faces of External Girders

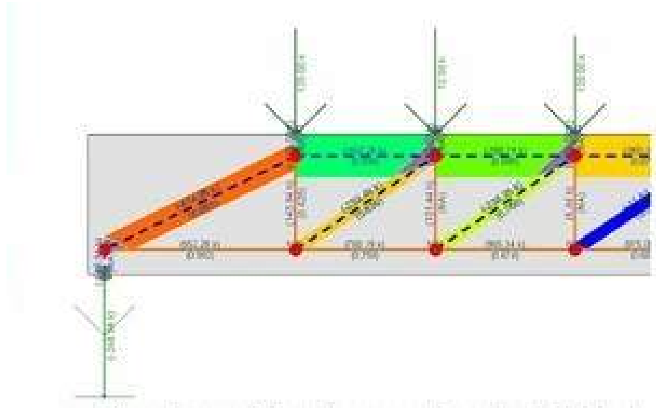
Review of Design and Construction Records

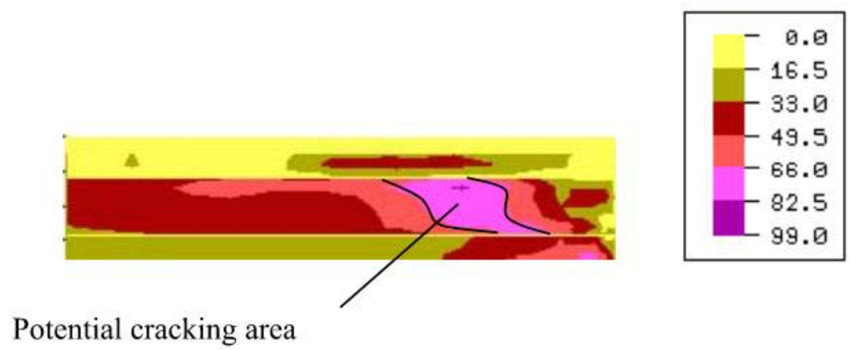
- Excessive Debonding due to Change Made in Construction
- 33 Strands in Bottom Flange
- 20 (61%) Debonded
- 13 (39%) Fully Bonded
- Current FDOT Codes Allow 25% Debonding, not to exceed 30%



Effect of Excessive Strand Debonding

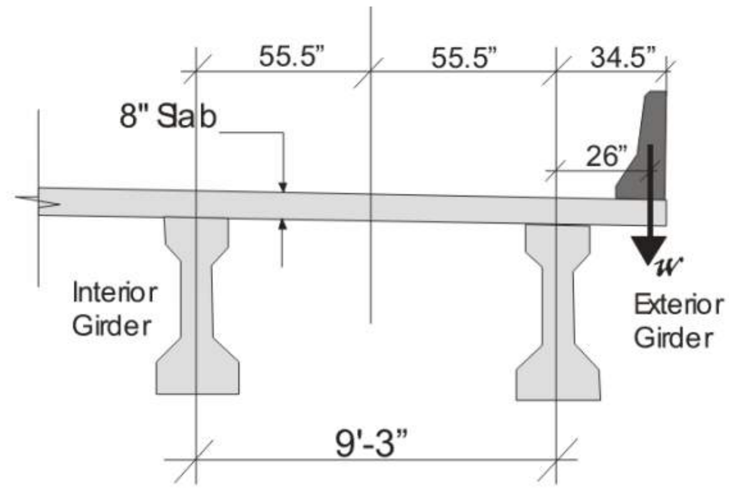
1. Traditional Shear Analysis with Standard AASHTO Specifications
2. Strut and Tie Model
3. Non-Linear Finite Element Model

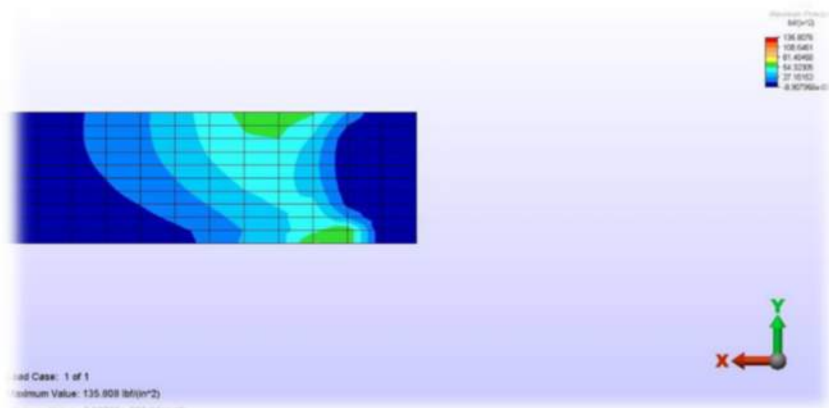




External Girders 93,98% and Internal Girders 1%

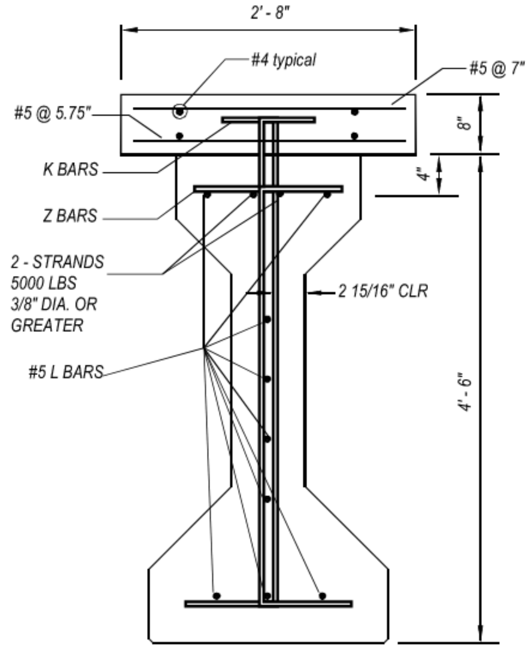
- Narrow outside overhangs
- Wide beam spacing
- Torqueing effect when the wet concrete load applied to beam
  - Torque remained in beams after concrete set
- Effect of Thermal Radiation
  - The 20º temperature differential created maximum principal stresses of 50 psi



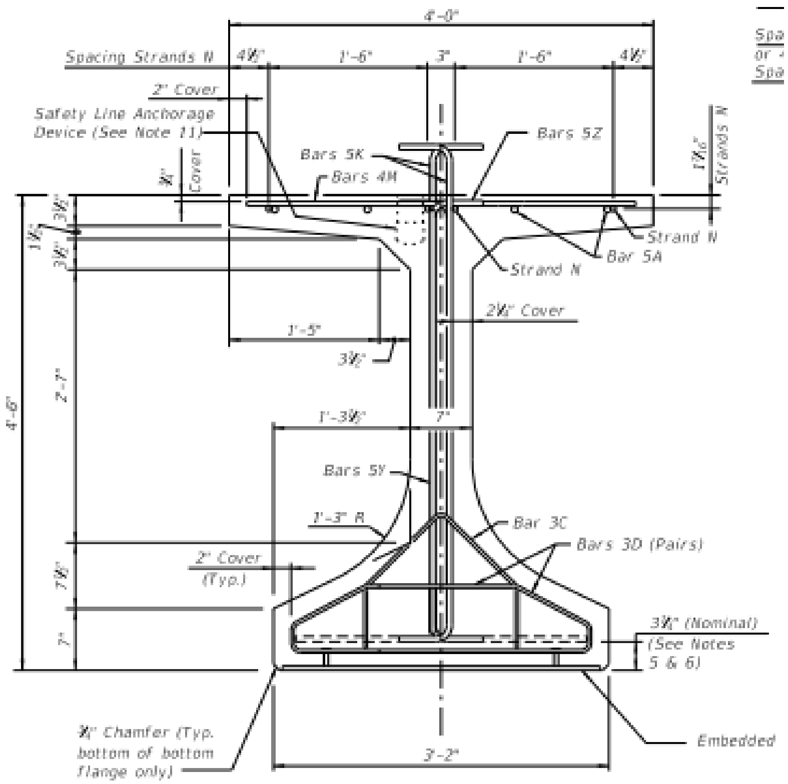


Direct Reason for Failures

- Excessive Debonding
- No Confining Steel



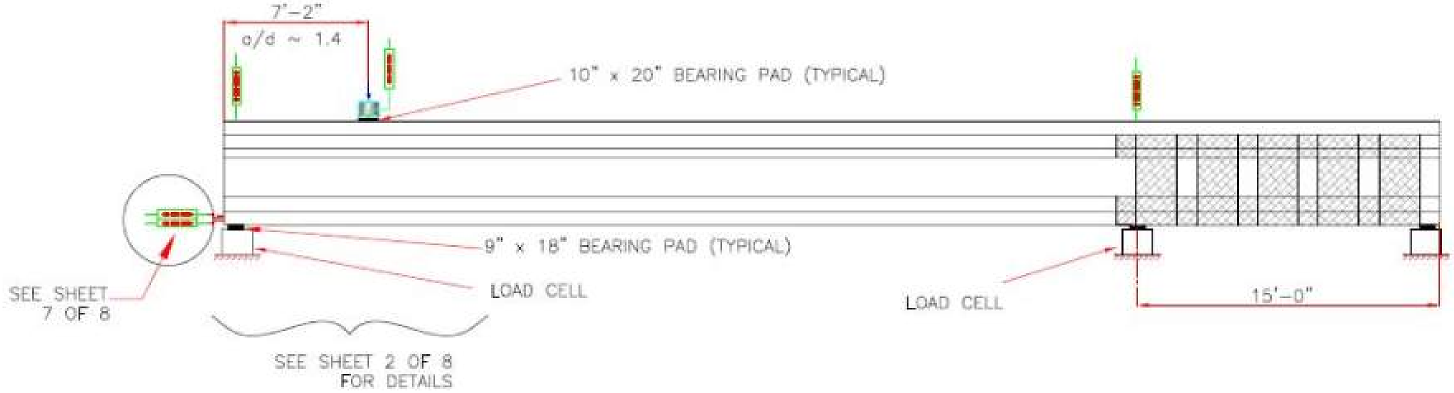
AASHTO TYPE IV (54")
Used on Skyway



Florida I-Beam (54")
Current Standard

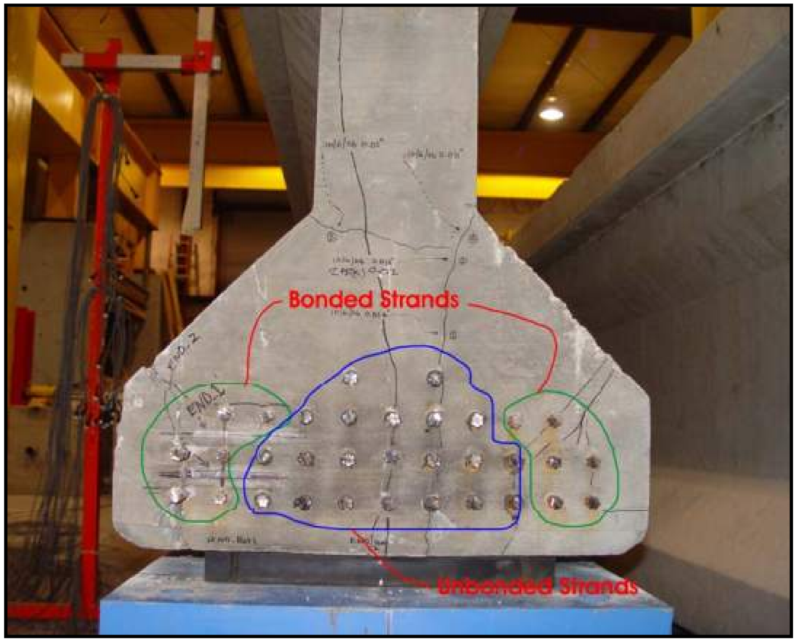
Girder Testing

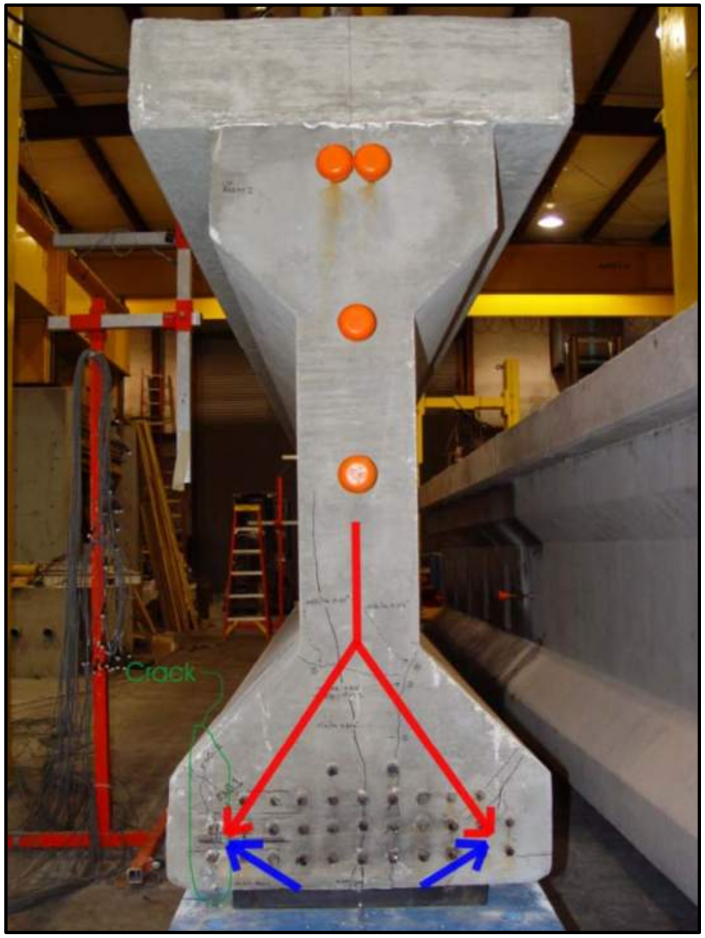
- Fabricated Two TYPE IV Girders
- Replicated Trestle Span Beams
- Identical Debonding
- Strengthened One Side
- Load Tested



Replicated AASHTO TYPE IV Girders

- Replicated Trestle Span Beams
- Identical Debonding
- Load Tested



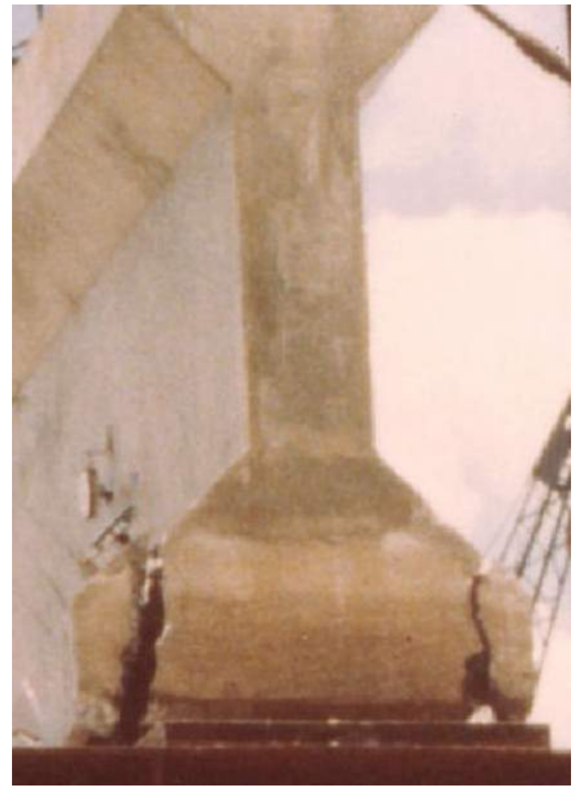


Testing Results

- All Four Tests Exhibited Same Failure Mode
- Bulb Cracking Pattern
- Caused by Excessive Debonding
- No Confinement Steel
- Bursting of the Bulb

Comparison of Testing

Structures Research Lab Testing



Beam Testing During Construction

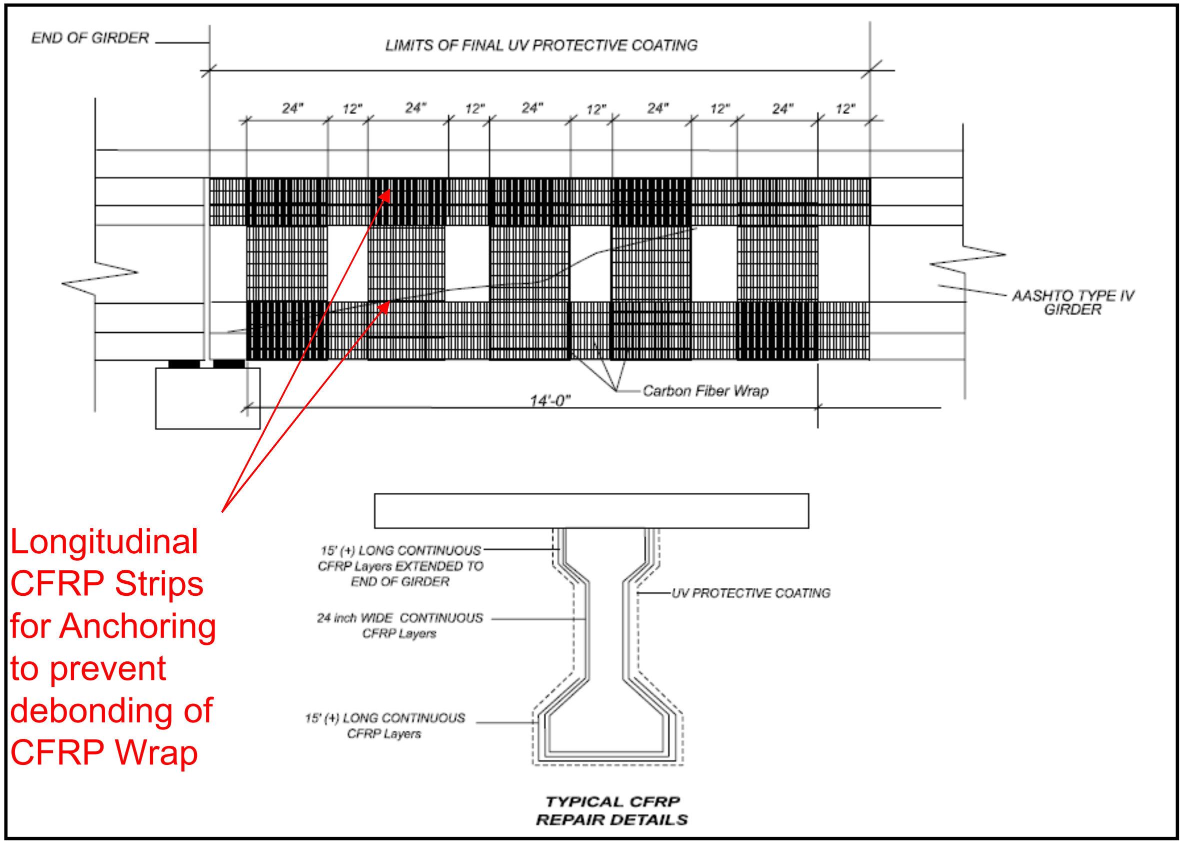
Conclusions and Recommendations of Studies

1. Diagonal cracking on exterior faces of external girders ≈ 98% and 93%; Interior girders ≈ 1.0%.
2. Traditional Analysis Indicates no deficiency in girders.
3. Standard AASHTO Specifications did not consider effect of debonding on shear capacity and overestimated nominal shear capacity of girders by 25%.
4. Strut and Tie Model and the Nonlinear FEM analysis are within 3%.
5. Concrete shear strength (Vc) insufficient to resist service loads.
6. CFRP strengthened and Control beams exhibit same patterns
7. CFRP Strengthened a/d Ratio = 1 → 9% Increase in Vc
8. CFRP Strengthened a/d Ratio = 3 → 21% Increase in Vc
9. CFRP Wrap Also Improves Confinement
10. Recommendation ➔ Structural Strengthening with CFRP Wrap

Project 1 (2007)

- 1st Strengthening Project
- Pilot Project
- Wrapping 965 LF
- Addressing 11% (worst) Cracked Beams

2007 CFRP Strengthening Plan



Concrete Surface Preparation

- Abrasive Blasting
- Grinding Corners
- Air Blasting

Epoxy Injection of Cracks

- Important to have uninterrupted surface area

CFRP Installation 2007

- Vertical Strips for Shear

CFRP Installation 2007

- Longitudinal Strips for Anchoring

NCHRP Report 678 (2011)

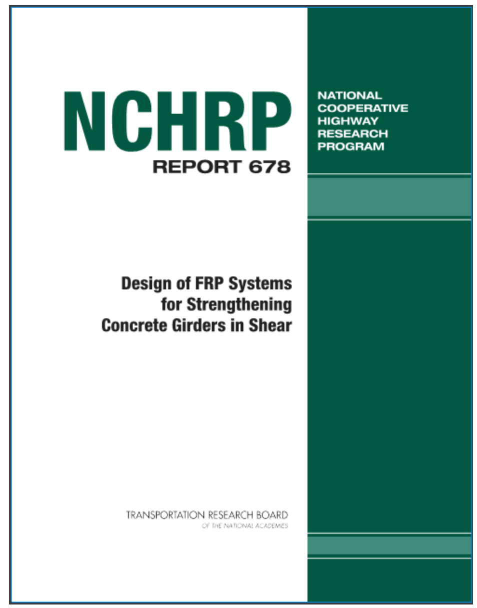
- FRP Design for Shear Strengthening
- Mechanical Anchoring
  - Most effective method to prevent debonding of FRP Wrap

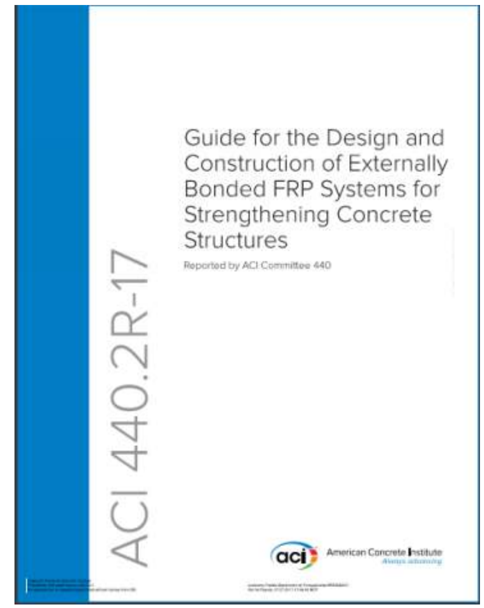
Project 2 (2013)

- Pilot for Mechanical Anchoring
- Wrapping 365 LF
- Addressing 4% (worst) Cracked Beams

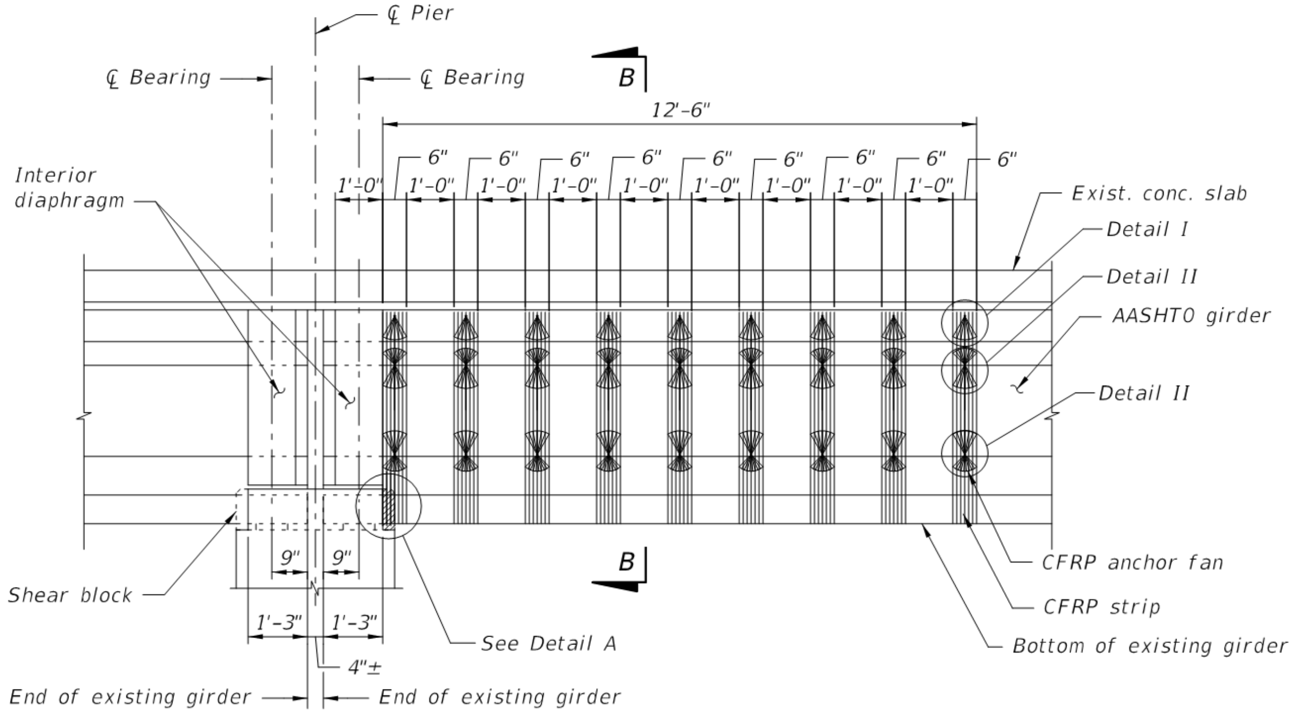
Project 3 (2019)

- Third and Final Project in the Series
- Wrapping 7,225 LF
- Addressing 85% Remaining Deficient Beams
- Designed with the most current standards and codes
- Used what has worked successfully
- Allowed for self-adhesive wrap



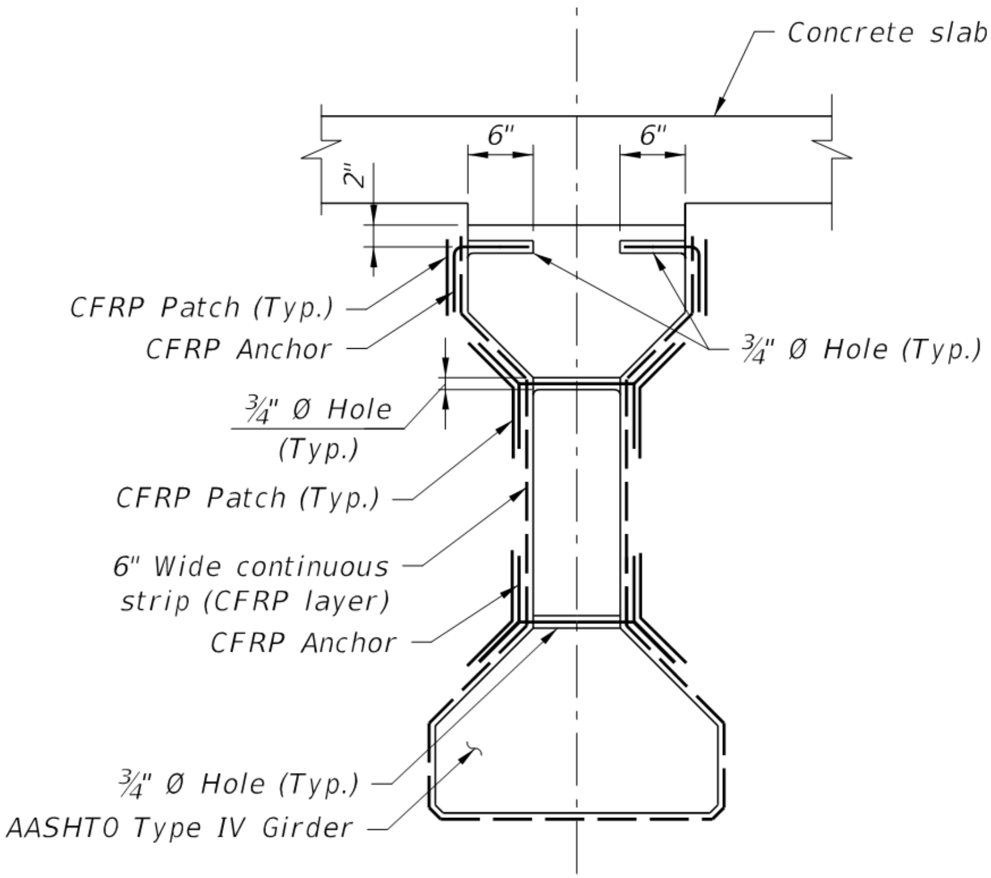


Strengthening w/Mechanical Anchoring



Strengthening w/Mechanical Anchoring

- Flange- 6" Both sides
- Web- All the way through



Holes for Mechanical Anchoring

Radius ground to ½” minimum

Epoxy Installation

CFRP Wrap Installation

- 6" Vertical CFRP Strips
- 12" Spacing

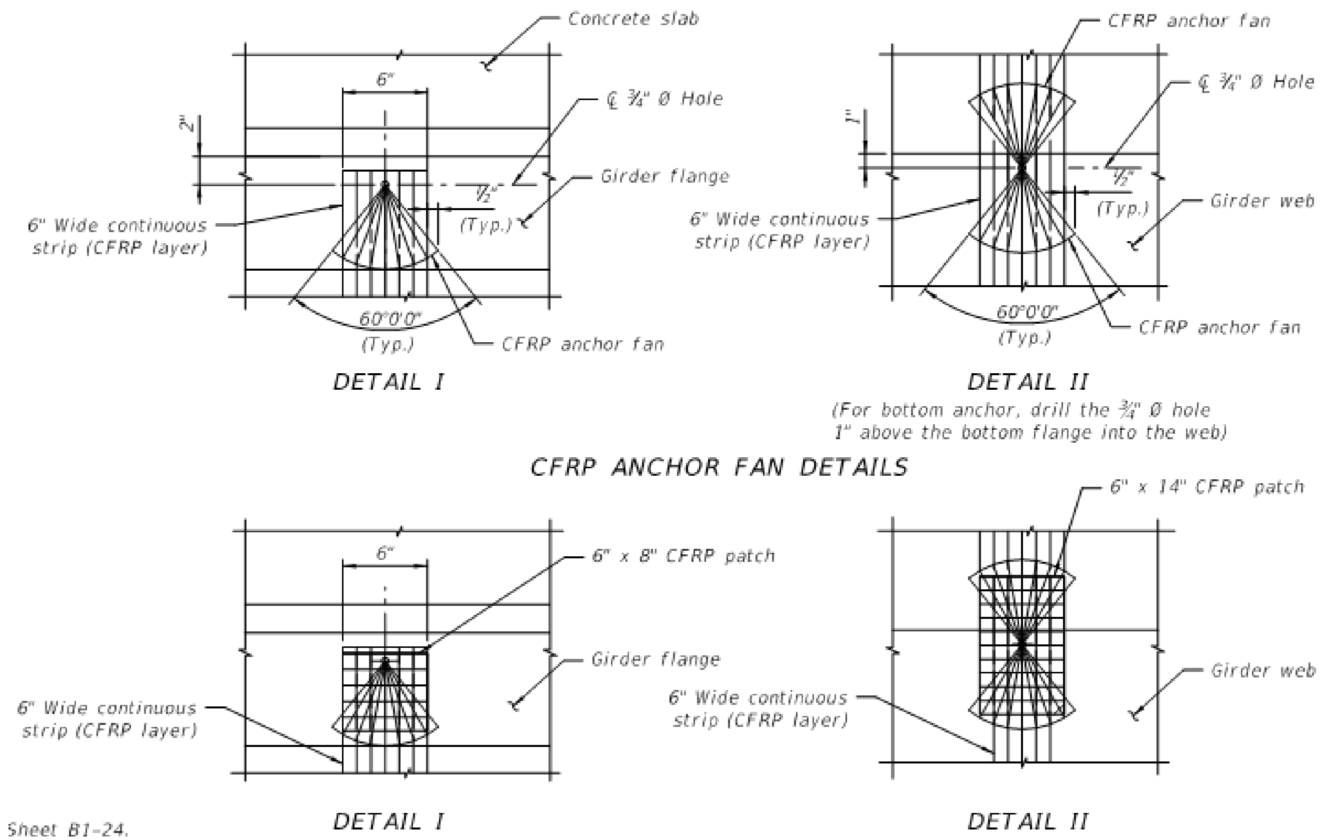
Pull-Off Testing

Strength ≥ 200 psi

CFRP Mechanical Anchors Installation

- Pulling CFRP mechanical anchors through the web
- Fanned out at ends

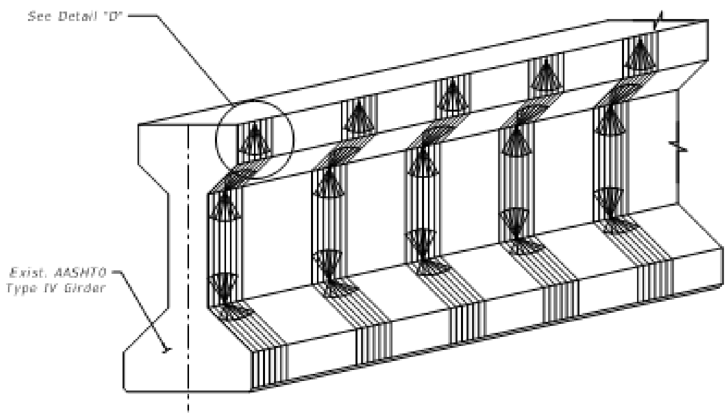
CFRP Strengthening w/Anchoring Plan

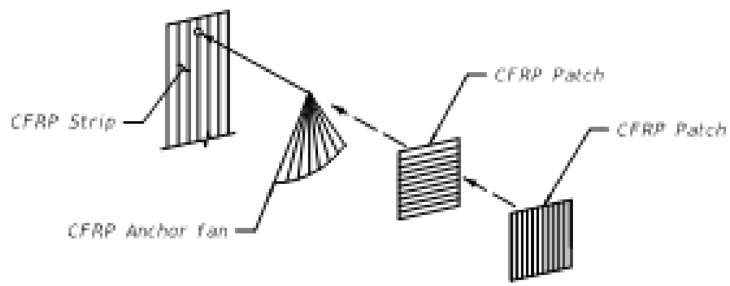


2013 CFRP Anchor Fans Installation

- Epoxy anchor fans to face of beam

CFRP Strengthening w/Anchoring Plan





DETAIL "D"

CFRP Patch Installation

- Epoxy CFRP patches over fans

CFRP Wrap, Anchors and Patch Installed

- Prior to Curing, Testing and UV Coating

UV Protective Coating

- UV Protective Coating installed over CFRP Material

Summary of Projects

Description	Year	Deficient Beams Addressed	CFRP Wrap (LF)
Pilot Project	2009	11%	975
Pilot for Mechanical Anchoring	2013	4%	365
Self-Adhesive CFRP Wrap	2019	85%	7,225

Acknowledgements

- Jim Jacobsen, PE, District Structures Maintenance Engineer, District 1 & 7 Structures Maintenance Office (DSMO)
- Ignacio Recio, PE, Skyway Bridge Maintenance Engineer, DSMO
- Mohsen Shahawy, PhD, PE, President - Chief Engineer, SDR Engineering, Principal Investigator for Cracking Investigation of the Girders of the Skyway Trestle Spans and EOR for 1st CFRP Project
- Teddy Theryo, PE & Tony Ledesma, PE / Parsons Brinckerhoff (EOR for 2nd CFRP Project)
- Steve Womble, PE, Senior Structural Engineer, T.Y. Lin International
- Jim Fitzer, PE / CEI Project Manager / AECOM (CEI for 2nd Project)
- Jaime Deese, PE (Keystone)/Marcus Kelley, PE & Dustin Spears, PE (Highspans), CEI for 3rd CFRP Project
- FDOT Structures Research Center, Initial Report on Testing of Simulated Skyway Trestle Span Beams
- H.R. Hamilton, G. Llanos, B. Ross, University of Florida, Authors of Shear Performance of Existing Prestressed Concrete Bridge Girders

Questions?